U. S. DEPARTMENT OF AGRICULTURE
WEATHER BUREAU
CHARLES F. MARVIN, Chief

MONTHLY WEATHER REVIEW

SUPPLEMENT No. 16

PREDICTING MINIMUM TEMPERATURES FROM HYGROMETRIC DATA

By J. Warren Smith, Meteorologist
And Others

WASHINGTON
GOVERNMENT PRINTING OFFICE
1920

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PREDICTING MINIMUM TEMPERATURES FROM HYGROMETRIC DATA.

INTRODUCTION.

By CHARLES F. MARVIN,

Chief U. S. Weather Bureau

The work done by Prof. J. Warren Smith in applying mathematical methods to the complex problems of the relation between weather and crops, or, as in this case, the prediction of minimum temperatures from data available the day before, is commended in the strongest way to meteorologists and to employees of the Bureau especially, as illustrating methods by which more or less indefinite relations may be reduced to convenient and practical mathematical terms. As I have recommended this method to Prof. Smith in lieu of the more tedious least square method, it may be proper to briefly point out the real contrasts and relations between these methods.

After preparing a graph or chart of given data, the problem is to find some form of curve that will represent the arrangement of dots with some satisfactory accuracy. Little can be said here in regard to the choice of line or curve. If a straight line seems to represent the data as well as any other, then the methods described in the MONTHLY WEATHER REVIEW for August, 1917, or the ordinary correlation methods, doubtless suffice. If, however, a form of curve is required, the choice becomes more complex. The parabola or possibly hyperbola may be the simplest forms to try, assuming that the curvature is not complex and with points of inflection.

Having chosen the type of curve, the next problem is to evaluate the unknown coefficients. It is a well-known principle in algebra that the values of unknown terms in equations can be calculated only when we have just as many independent simultaneous equations between the quantities as there are unknown terms to be found.

Least square method.—The least square method is simply a mathematical scheme by which a large number of observations may be combined in a manner which will give the required number of so-called "normal" equations and at the same time according to a principle which will give the "best fit."

The expression "best fit" is incapable of rigorous definition; however, it is a very useful term and must be properly understood and used. Technically, the "fit" of a curve to any series of observations upon related quantities may be measured by the sum of the squares of the residuals (differences between the observed values and those calculated by the equation on trial). The best of several equations is the one for which the sum of squares of the residuals is a minimum, or we may just as well note that the so-called standard deviation[1] will also be a minimum at the same time. The latter as a measure of fit is preferable because it permits comparing results based on data comprising different numbers of observations.

When the type of equation is chosen (a straight line, parabola, or other curve) the least square solution gives at once the particular line of that type which fits best, but whether some other type of line will fit still better can be found out only by trial, that curve being the best for which the standard deviation is a minimum.

The use of the least square method is generally tedious and laborious, especially when large quantities of data must be treated and when three or more unknowns are to be found. It must, however, be employed in many cases. On the other hand, the present problem and many others of similar character may be solved much more expeditiously and without sacrifice of useful accuracy by what I have called the "star" point method, in order to clearly differentiate it from the least square method. It may be applied to the solution of any problem and supplies the required number of independent "star" equations simply by the judicious location on the graph of the required number of "star" points, one for each unknown to be evaluated. (See fig. 2.) This method simply substitutes intelligent selection of "star" points for the tedious least square process of forming normal equations, with the further convenience that in general the numerical factors are small numbers, thereby simplifying the solution of the equations.

It seems proper to add a word of advice to beginners in regard to securing accuracy in arithmetical computations. In general, the accuracy of a numerical value is measured by the number of significant figures, and this has no connection whatever with the position of the decimal point. The number 893, for example, is much more accurately expressed than the number .0035, although the latter may be a very minute quantity. In problems of the kind under consideration it is generally necessary to carry four, or possibly five, significant figures throughout the original computations, inasmuch as this makes the derived results sufficiently accurate to show serious disagreement if errors of arithmetic are made in the process. At the end of the operation unnecessary significant figures may be dropped by the usual rules. The effect of this may, however, appear by seeming to shift the calculated curve so as not to pass exactly through the original star points, as should otherwise be the case.

[1] MONTHLY WEATHER REVIEW, 1916, vol. 44: 557.

PREDICTING MINIMUM TEMPERATURES FROM HYGROMETRIC DATA.

By J. Warren Smith, Meteorologist, Chief of Division of Agricultural Meteorology.

[Dated Washington, D. C., July 18, 1919.]

In the Monthly Weather Review for August, 1917 (pp. 402–407), the writer discussed the prediction of minimum temperatures on radiation nights by the use of the linear equation

$$y = a + bR,$$

using R as the evening relative humidity, and y as the variation of the night minimum temperature from the evening dewpoint. This equation was applied to hygro-

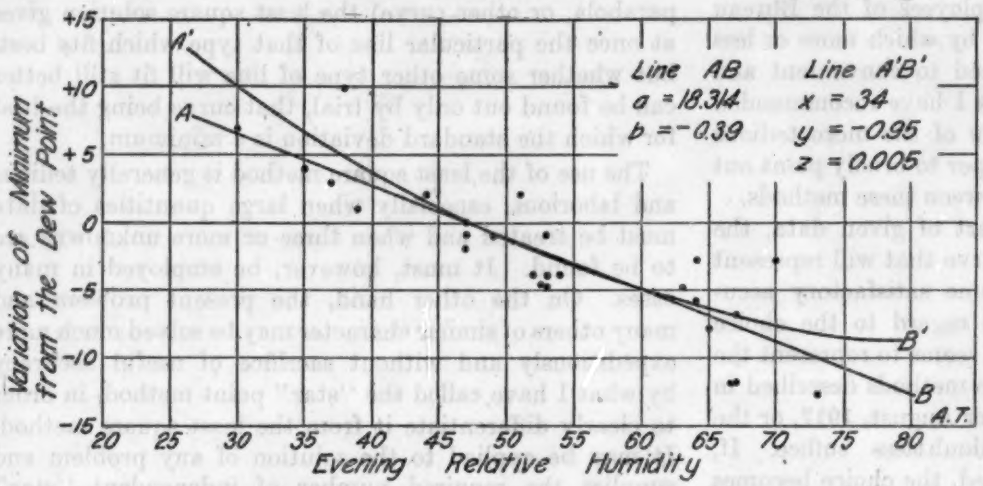

Fig. 1.—Germantown, Ohio, March to June, 1915. Relation between the evening relative humidity and the variation of the minimum temperature during the night from the evening dew point.

metric data obtained at special fruit stations in Ohio, and the results were found to be very satisfactory.

In the attempt to use this equation at other places, however, local forecasters found that it did not give satisfactory results.

Upon making dot charts from these data at other stations it was found that the dots were arranged in the form of a curve, instead of along a straight line, hence the linear equation does not give the line of closest fit.

As the deviation from a straight line is fairly regular, and in many cases is not great, and as the next simplest assumption to the straight line in this case is the parabolic curve, the next step taken was to determine the coefficients of equation for this type of curve.

THE EQUATION FOR A PARABOLA.

The equation of a parabola may be written

$$y = a + bx + cx^2$$

in which the coefficients a, b, and c are commonly designated as constants whose values are either known beforehand or must be determined in order that the curve may fit some particular case. The quantities x and y may have almost any values in pairs and are called variables. For some arrangements of data the equation might need to be written

$$x = a + by + cy^2,$$

but the same result would be gained simply by transposing the scheme of plotting the data. Inasmuch as the last letters of the alphabet are commonly used to designate unknown quantities, we have changed the first equation to read

$$v = x + by + cz$$

in which x, y, and z are the coefficients to be determined; b is the evening relative humidity, c the square of the relative humidity, and v the variation of the minimum temperature of the following morning from the evening dew point, or the value desired in making a forecast of the minimum temperature on radiation nights.

METHOD OF OPERATION.

The first step in working out the formula for predicting the minimum temperature from the hygrometric data, as well as in other correlation work, is to chart the available data as indicated in figures 1 and 2, using only radiation nights.

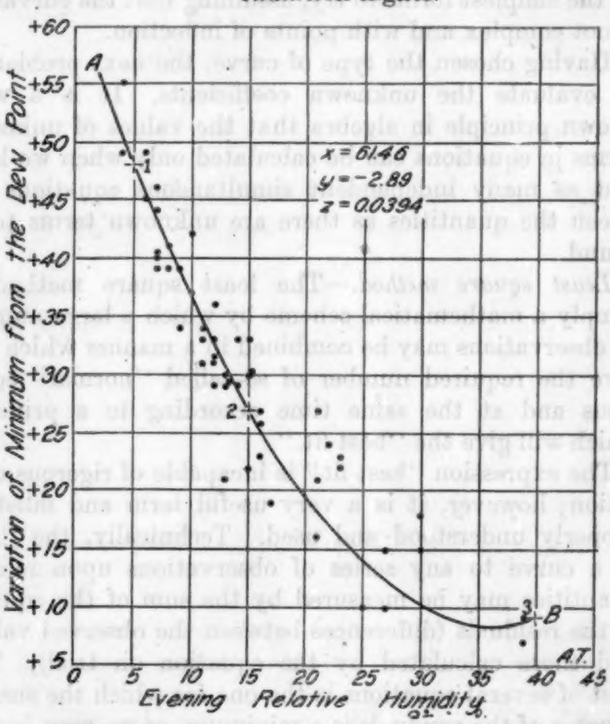

Fig. 2.—El Paso, Tex., March, April, and May, 1918. Parabolic curve.

The relative humidity data, as determined by the evening observation of the dry and wet bulb temperatures, are indicated at the bottom of the diagram, while the

figures entered at the left are the differences between the dew-point temperature at the evening observation and the minimum temperature of the following night.

A dot is entered on the diagram for each day covered by the record to agree with the observed relative humidity and variation of the minimum from the dew-point temperature. If the dots arrange themselves as in figure 1, it seems as if a straight line is as good a fit as any other, and in such cases the linear equation

$$y = a + bR,$$

as explained in the article referred to (MONTHLY WEATHER REVIEW, August, 1917), will be a satisfactory one to use in calculating the probable minimum temperature from the evening hygrometric data.

In this equation the values of a and b are the unknown quantities to be determined, and in the Germantown table they were found to be 18.31 and -0.39, respectively. The calculation of the straight line of nearest fit by the insertion of these values in the equation

$$y = a + bR,$$

in which R is the evening relative humidity and y the variation of the minimum from the evening dew point, gives the line $A\,B$ on figure 1.

In figure 2, however, it was evident at once after completion of the dot chart that a straight line would not give as close a fit as some form of curve. The type of curve is not known, but we may assume the data may be represented by some portion of some parabola which is perhaps the simplest type of curve likely to be suitable. The problem, then, is to obtain the constants for such an equation.

CALCULATING THE PARABOLIC CURVE—"STAR POINT METHOD."

The process for calculating this curve is given somewhat in detail, so that forecasters and others may become familiar with it and use it in the solution of problems at their own stations:

Make a judicious selection of three "star" points, as 1, 2, 3, figure 2. These must be judged to be highly representative of all the data, but the points can generally be chosen so that the coordinates are simple numerical quantities:

After the selection of the relative humidity values to be used in these equations, the values of v, or the exact location of the points 1, 2, and 3, can be determined by inspection or by calculation from the position of the surrounding dots.

At 1 the relative humidity is 5 per cent, and the variation of the minimum temperature from the dew point 48°.

At 2 the relative humidity is 15 per cent, and the variation 27°.

At 3 the relative humidity is 40 per cent, and variation 9°.

With these data the normal equations are written as in Table 1.

TABLE 1.—*Normal equations.*

b	v	c
5	48	25
15	27	225
40	9	1600

b=relative humidity.
c=square of relative humidity.
v=variation of minimum temperature from the dew point.

From this table the three equations for solving the unknown factors x, y, and z are written as follows:

(1) $x + b_1y + c_1z = v_1$

(2) $x + b_2y + c_2z = v_2$

(3) $x + b_3y + c_3z = v_3$

The coefficients b_1, b_2, and b_3 represent the three values of b in Table 1, viz, 5, 15, and 40; the values of c and v, etc., are the corresponding values of these factors in Table 1.

The values of x, y, and z will be determined by the usual algebraic methods of solving for unknown quantities. This may be done by indicating the work algebraically and solving for each value, or preferably by what may be termed the "Direct solution method."

DIRECT SOLUTION.

Insert the values under b, v, and c in Table 1 in equations (1), (2), and (3), and solve for z as follows:

(1) $x + 5y + 25z = 48$

(2) $x + 15y + 225z = 27$

(3) $x + 40y + 1600z = 9$

Subtracting equation (2) from equation (1) we get

(4) $-10y - 200z = 21.$

Subtracting (3) from (2) we have

(5) $-25y - 1375z = 18.$

Obtain like coefficients for y by multiplying equation (4) by 5, and equation (5) by 2, when we get, respectively,

(6) $-50y - 1000z = 105$, and

(7) $-50y - 2750z = 36.$

Subtracting equation (7) from equation (6), we have

(8) $1750z = 69$, or

$z = 0.03943.$

TO DETERMINE THE VALUE OF Y AND X.

The next step will be to substitute the value of z in equation (4) or (5), and solve for y. The work will be checked by solving for y in both equations, and this should be done. Substituting the value of z in equation (4), we get

(9) $-10y - (200 \times 0.03943) = 21.$

$-10y = 21 + 7.886.$

$-10y = 28.886.$

$y = -2.8886.$

Substituting z in equation (5), it becomes

$$(10)\qquad -25y-(1375\times 0.03943)=18$$
$$-25y=18+54.21625$$
$$-25y=72.21625$$
$$y=-2.88865$$

These values of y must agree closely if the arithmetic is correct. Substituting the values of y and z in equations (1), (2), and (3), we get the following

$$(11)\qquad x+(5\times -2.8886)+(25\times 0.03943)=48$$
$$(12)\qquad x+(15\times -2.8886)+(225\times 0.03943)=27$$
$$(13)\qquad x+(40\times -2.8886)+(1600\times 0.03943)=9$$

Carrying out the calculation we have for each equation, respectively,

$$x=61.45725$$
$$x=61.45725$$
$$x=61.456,\text{ or an average of}$$
$$x=61.457$$

In general, it will be best to check the accuracy of all the arithmetic in the computation of coefficients. This is done by substituting values of x, y, and z in equations (1), (2), and (3), which should give exactly the absolute terms, in this case 48, 27, and 9. Very slight errors will result from dropping digits in the values of x, y, and z, but appreciable discrepancies indicate arithmetical errors.

THE HYGROMETRIC EQUATION FOR EL PASO, TEX.

By using these values

$$x=61.46$$
$$y=-2.89$$
$$z=0.0394$$

for the unknown quantities in the equation

$$v=x+by+cz$$

the probable variation of the minimum temperature from the evening dew point (v) can be determined on radiation nights with a fair degree of accuracy at El Paso.

The parabolic curve will be placed on diagram 2 by utilizing the points already selected and calculating others by this equation. For a relative humidity of 10 per cent, for example, by inserting the known values of b and c, and the above-determined values for x, y, and z, in the equation

$$v=x+by+cz$$

it becomes

$$(14)\qquad v=61.46+(10\times -2.89)+(100\times 0.0394)$$

carrying out the calculation we get

$$v=36.5^\circ$$

By the same method the value of v for other relative humidity figures is calculated, and then the line $A\ B$ drawn.

If the line, as calculated, runs too high or too low, it will be evident that the points for making the three normal equations were not wisely chosen, and new points must be taken and the work repeated.

If trials fail to give a satisfactory parabolic curve, it will be evident that the line of satisfactory fit is not a parabola, but some other curve. Just as the trial of a parabolic curve to fit the data shows a closer agreement than a straight line, so the trial of some other curve than the parabola might show still a better fit, as explained in the introduction.

PRACTICAL APPLICATION OF FORMULA.

Having satisfied oneself that a particular formula is a dependable aid in predicting minimum temperatures, the use of the equation in practical work is effected most expeditiously by computing a table or preparing charts giving the necessary values either of v, which is the variation of the minimum temperature from the dew point for a series of values of b, or providing a larger table or a chart giving directly the value of the minimum temperature based on the known values of b and the dew point as indicated in the table below:

EL PASO, TEX.

(See fig. 2.)

$$v=x+by+cz$$
$$x=61.457,\ y=-2.889,\ z=0.03943$$

b	c	by	cz	v
5	25	− 14.445	0.986	48.00
6	36	− 17.334	1.3184	45.44
7	49	− 20.223	1.9306	43.16
8	64	− 23.112	2.5216	40.87
9	81	− 26.001	3.1914	38.65
10	100	− 28.89	3.943	36.51
20	400	− 57.78	15.767	19.44
30	900	− 86.67	35.487	10.27
40	1,600	−115.56	63.088	8.99
50	2,500	−144.45	98.575	15.58

Where many observations are available it may be found necessary simply to make the dot charts and then draw the curve of nearest fit free-hand without making the calculation, and use this in future work. If one wishes to use the formula at other places with a similar topography, however, the curve should be calculated and the table made as above.

For the purpose of study also, as well as to determine which type of curve gives the best fit, especially if humidity values outside of those already recorded are possible, it is always best to calculate the curve of nearest fit. At Germantown, for example, the parabola $A'\ B'$, apparently gives a better fit than the straight line $A\ B$. See fig. 1.

WILL THE PARABOLIC CURVE APPLY ELSEWHERE?

The next step in this inquiry was to chart hygrometric data at other places to see whether the parabolic curve is the line of nearest fit, and finally to ascertain whether similar curves fitted the data, so that the same values of x, y, and z may be used at places where the wet and dry bulb temperature records cover a very short period.

The following diagrams show the charted hygrometric data with the parabolic curve drawn as calculated from the data given on the diagram. It is deemed unnecessary to give the details of the work as it followed the procedure used in explaining figure 2.

Agriculture College, New Mexico.—Most regular Weather Bureau stations are located in large cities, where radiation is interrupted, hence the data for these studies were

collected mainly from regular and special stations surrounded, as far as possible, by rural conditions.

The chart and parabolic curve for the data at Agricultural College, New Mexico, show that the dots are noticeably more scattered than in the case of El Paso, which may possibly arise from less care or experience in taking the original hygrometric observations. While the parabola resembles the one for El Paso, the values of the unknown quantities are so different that the same equation can not be used at both places. For the college station for March to May, 1916–17, they are: $x=53.3$, $y=-3.9$, $z=0.0867$.

Boise, Idaho.—Figure 3 is for the observations taken on the lawn at Boise, Idaho, from April 1 to June 15, 1918. The most important thing about the chart is that the curve fits the data for *all* nights, as well as that for clear nights, with a few exceptions. This is also the case at Medford, Oreg.; and if it is found to be true elsewhere, it will prove to be an important aid in making minimum temperature estimates. A similar chart taken from the hygrometric data in the shelter on the roof of the office building, 70 feet above the ground, shows that the curves occupy about the same position when the relative humidity is low, but when it is moderately high

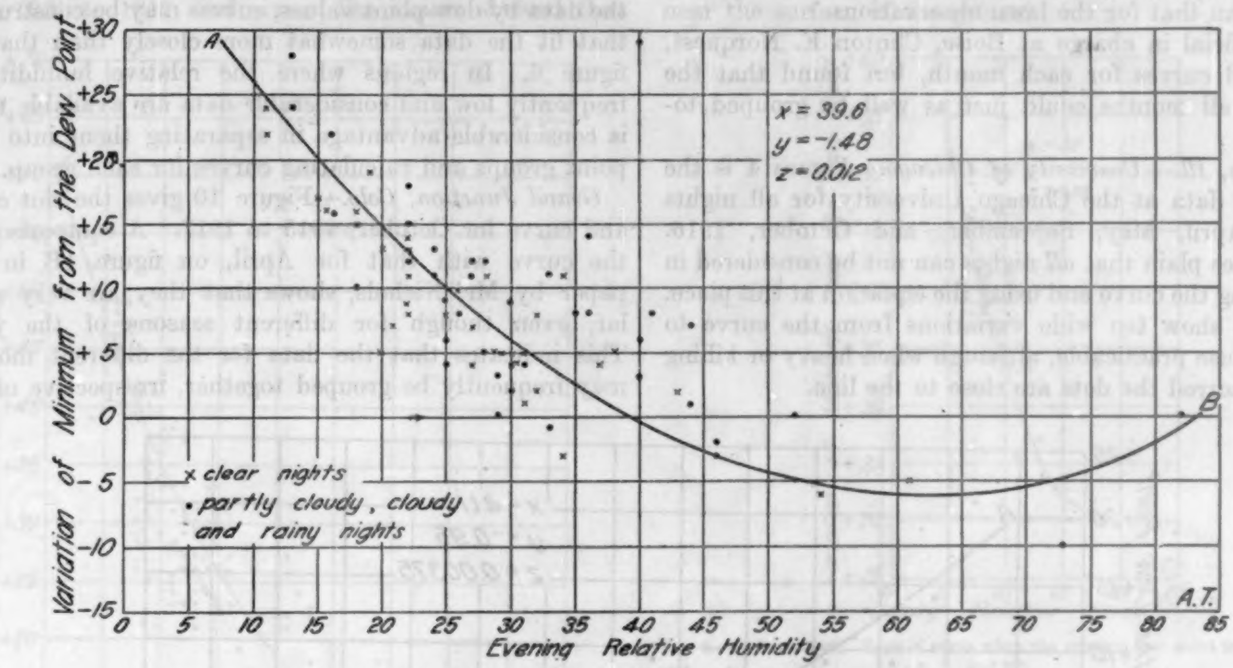

FIG. 3.—Boise, Idaho, April 1 to June 15, 1918. Observation taken on the lawn.

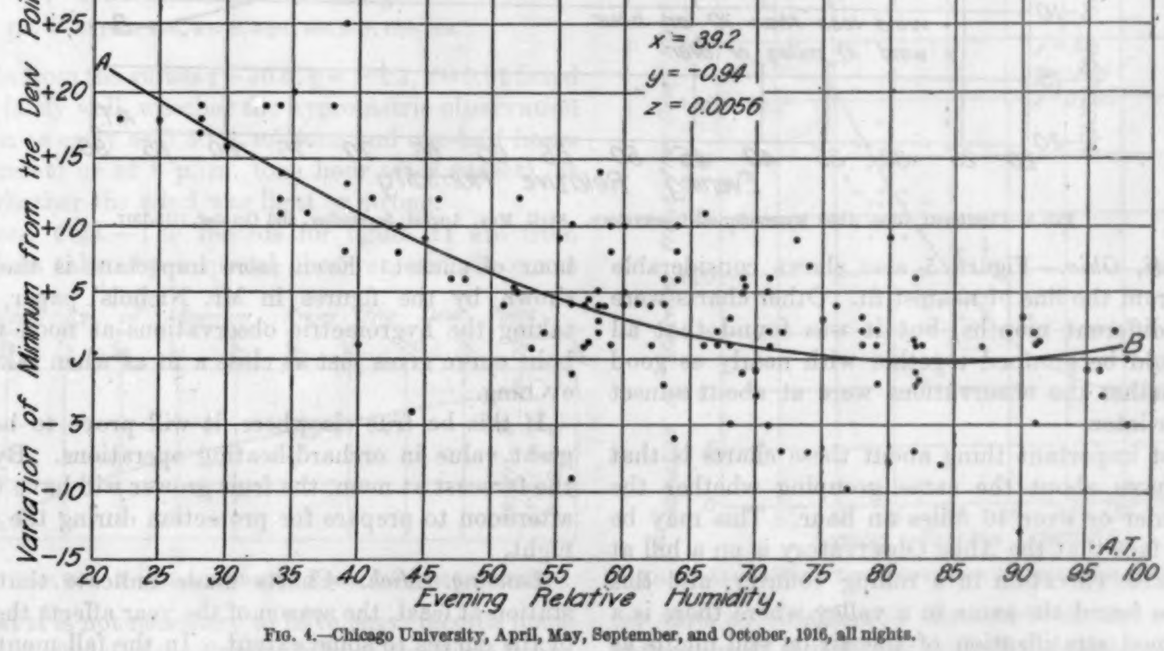

FIG. 4.—Chicago University, April, May, September, and October, 1916, all nights.

the roof curve is elevated somewhat. This results in a slightly different value for the quantities x, y, and z in the equations. These are: $x=37.1$, $y=-1.32$, $z=0.0117$. The roof curve fits the data for all nights even better than that for the lawn observations.

The official in charge at Boise, Clinton E. Norquest, calculated curves for each month, but found that the data for all months could just as well be grouped together.

Chicago, Ill.—University of Chicago.—Figure 4 is the chart for data at the Chicago University for all nights during April, May, September, and October, 1916. This makes plain that *all* nights can not be considered in calculating the curve and using the equation at this place. The dots show too wide variations from the curve to make its use practicable, although when heavy or killing frosts occurred the dots are close to the line.

March, April, and May, 1916 to 1918. The two curves *A B* are practically the same, but there are a few dots farther away from the curve on chart 6.

Figures 7, 8, and 9 show, however, that by grouping the data by dew-point values, curves may be constructed that fit the data somewhat more closely than that on figure 6. In regions where the relative humidity is frequently low and considerable data are available there is considerable advantage in separating them into dew point groups and calculating curves for each group.

Grand Junction, Colo.—Figure 10 gives the dot chart and curve for October, 1915 to 1917. A comparison of the curve with that for April, on figure 1B in the paper by Mr. Nichols, shows that they are very similar, even though for different seasons of the year. This indicates that the data for the different months may frequently be grouped together, irrespective of the

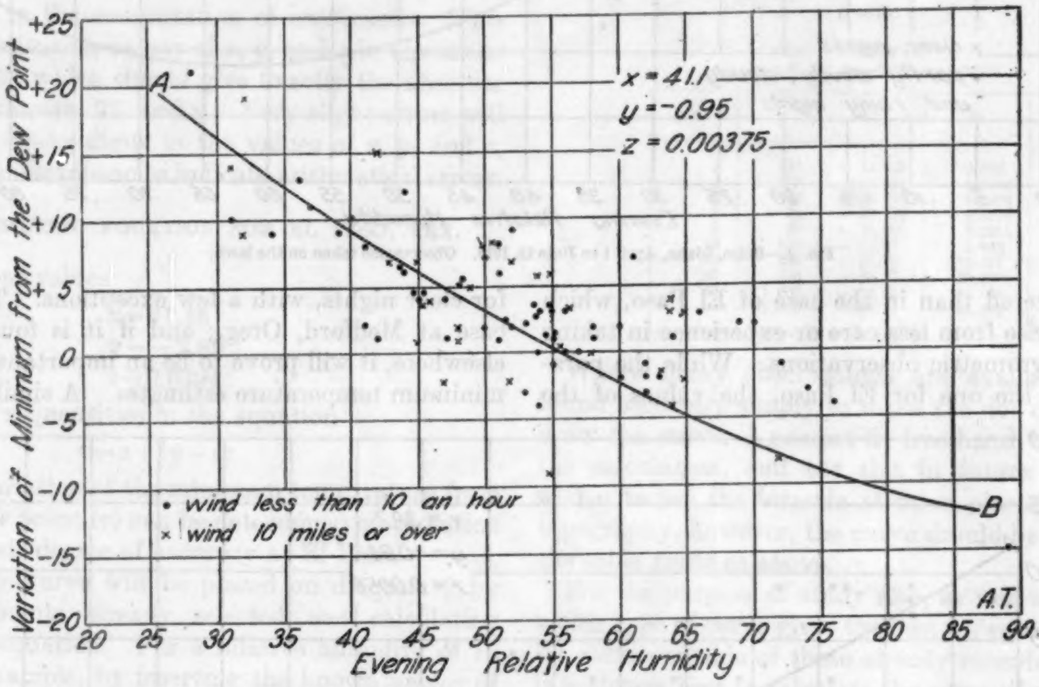

FIG. 5.—Cincinnati, Ohio, Abbe Meteorological Observatory. April, May, August, September, and October, 1915-1917.

Cincinnati, Ohio.—Figure 5 also shows considerable variation from the line of nearest fit. Other charts were made for different months, but it was found that all months could be grouped together with nearly as good results, whether the observations were at about sunset or one hour later.

The most important thing about these charts is that the dots have about the same grouping whether the wind is under or over 10 miles an hour. This may be due to the fact that the Abbe Observatory is on a hill at a considerable elevation in a rolling country, and this may not be found the same in a valley where there is a better defined stratification of the air on still nights as compared with windy ones.

El Paso, Tex.—Figure 2 gives the data at El Paso, Tex., for the spring months in 1918, while figure 6 covers

hour of sunset. Even more important is the fact, as shown by the figures in Mr. Nichols' paper, that by taking the hygrometric observations at noon the parabolic curve gives just as close a fit as when taken in the evening.

If this be true elsewhere, it will prove to be of very great value in orchard-heating operations. By making the forecast at noon, the fruit grower will have the whole afternoon to prepare for protection during the following night.

Lansing, Mich.—Charts made indicate that, at this station at least, the season of the year affects the position of the curves to some extent. In the fall months, when the observation is made about 90 minutes after sunset, the values are: $x=50.4$, $y=-1.317$, $z=0.00767$. In the spring months, when the observations were made about

sunset, they are: $x=39.2$, $y=-0.967$, $z=0.00467$. The same curve will not quite fit the two charts.

Modena, Utah.—Data were available at this station for May 1 to 31, and from September 1 to October 31, from 1905 to 1917, inclusive. The charts showed that

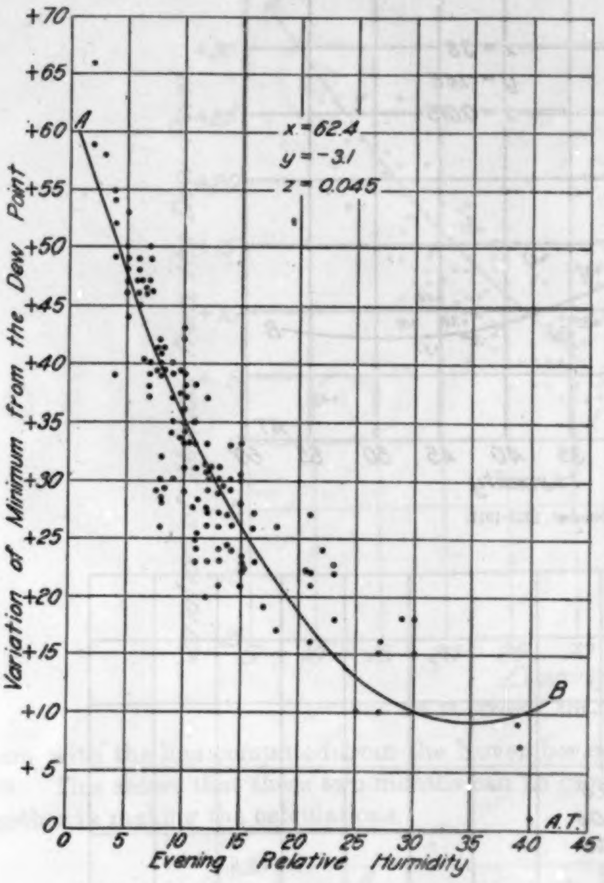

FIG. 6.—El Paso, Tex., March, April, and May, 1916-1918.

a parabola from the values $x=36.0$, $y=-1.3$, $z=0.01$ fitted the data fairly well, whether the hygrometric observation was taken as early as 5:30 p. m. (one and one-half hours before sunset) or at 8 p. m. (one hour after sunset), as well as whether the wind was light or strong.

Montrose, Colo.—The records for figure 11 are from observations taken by a special observer, and the curve

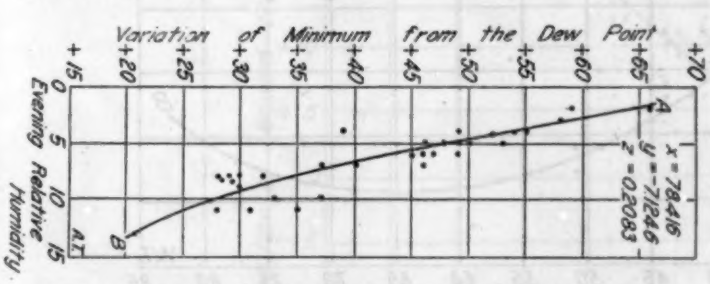

FIG. 7.—El Paso, Tex. Type of curve when the evening dew point is below 10°.

shows that it is not necessary to have these records made by a trained official of the Bureau to have the curve fit the data fairly well. With few exceptions a very good estimate can be made of the probable minimum temperature by the parabolic curve.

Phoenix, Ariz.—The data at this station were furnished for all radiation nights from December, 1914, to June, 1916, for the roof exposure, 76 feet above the ground, and from June, 1916, to July, 1917, for observations taken near the surface of the ground.

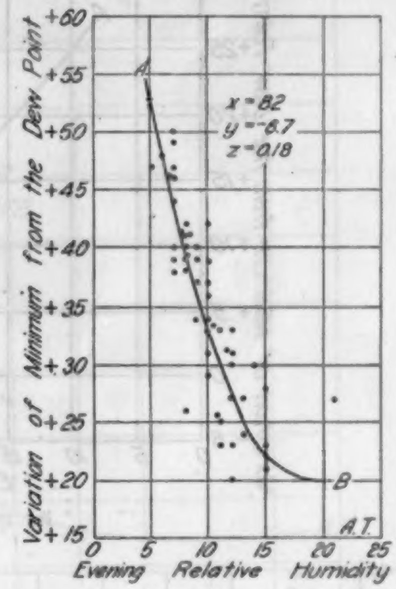

FIG. 8.—El Paso, Tex. Type of curve when the evening dew point is between 10° and 20°.

Figure 12 gives the dot chart and parabolic curve for all radiation nights for each month during the year at the ground station. Sunset at this station varies from two hours before the observation hour in December to about the observation time in midsummer. While there are a

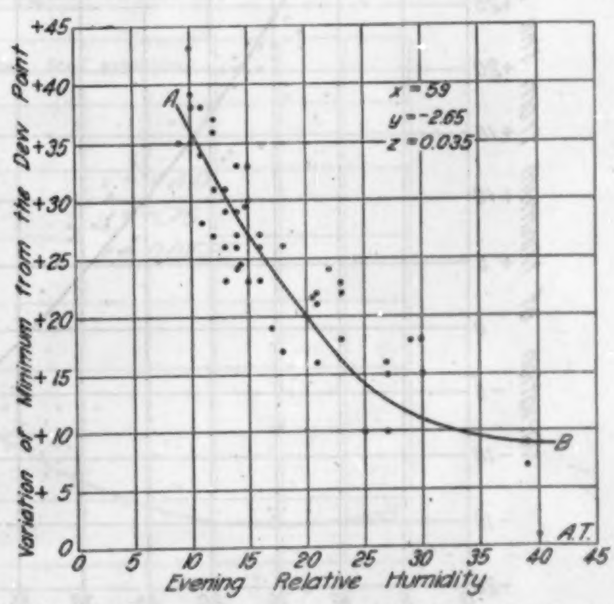

FIG. 9.—El Paso, Tex. Type of curve when the evening dew point is above 20°.

few dots at considerable distance from the curve, they are within 3° of it 70 per cent of the time.

The chart for the roof exposure for all radiation nights from December, 1914, to June, 1916, gave a closer grouping of the dots than on chart 12, but a parabola does not

fit the data so well. As the humidity values are highest in the winter months and lowest in the summer, it was evident that better results would be obtained by separating the seasons.

dew point is high and the relative humidity moderately low, the temperature fall will be greater than shown by the dots are within 3° of the curve 83 per cent of the time. A further analysis of these data shows that when the

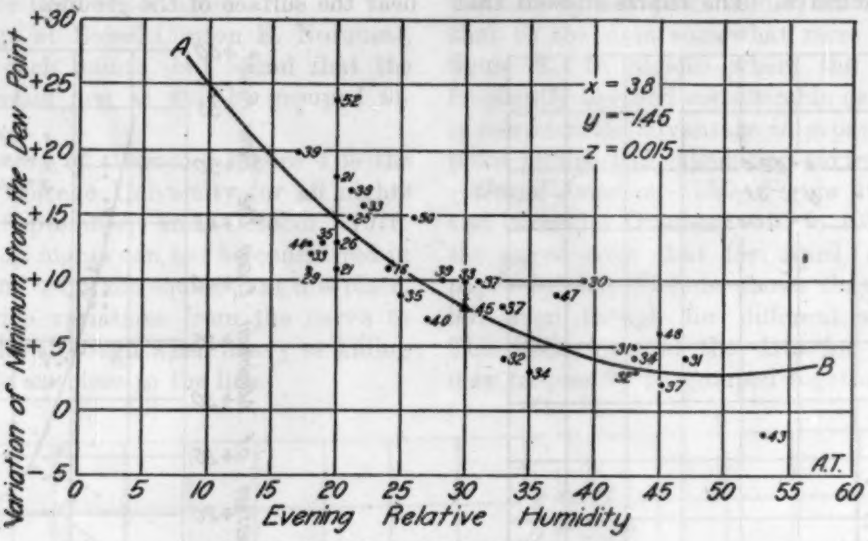

FIG. 10.—Grand Junction, Colo., October, 1915-1917.

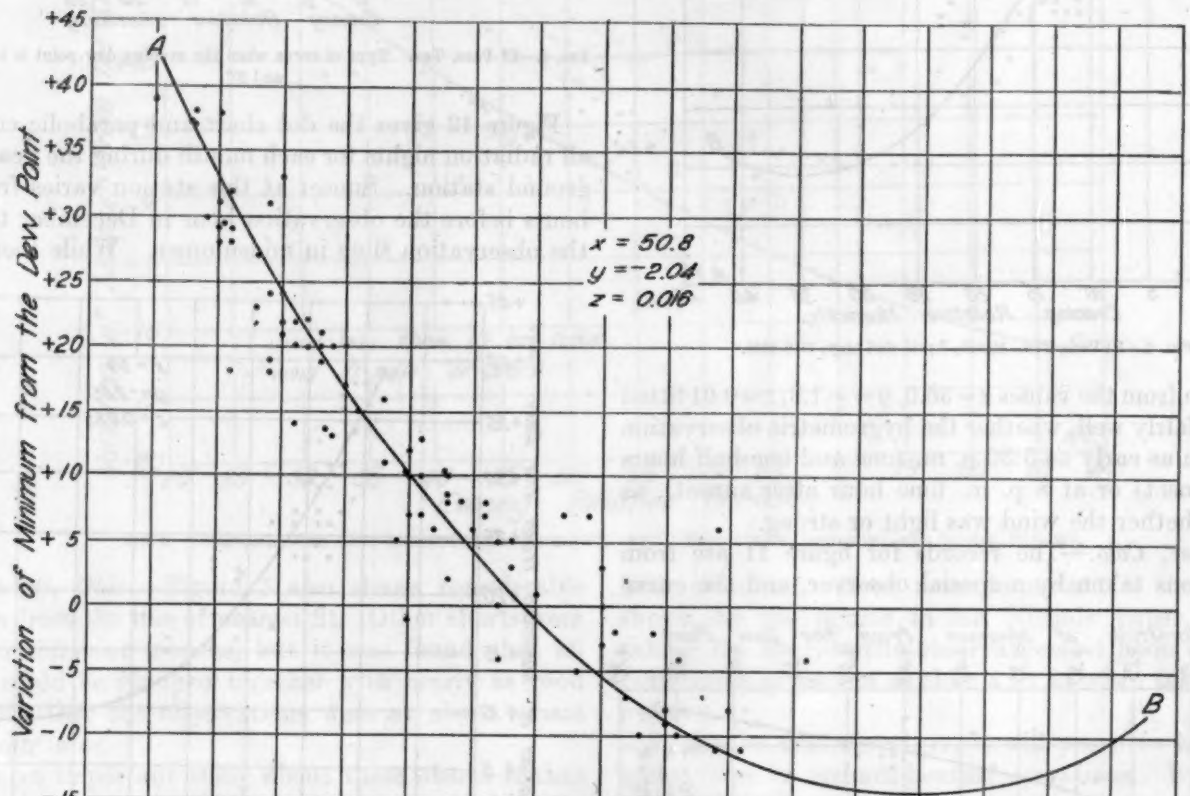

FIG. 11.—Montrose, Colo., April and May, 1890-1893 and 1918.

Figure 13 was, therefore, prepared for the months of November to March, inclusive, for the roof exposure. This demonstrates that the conclusion is a correct one and that the formula will prove of value at this station, as

the curve, but when both are low, the temperature will not fall so low as the formula will indicate.

San Diego, Calif.—A large amount of data was furnished by H. F. Alcitore, the official in charge at San Diego,

and he has made important contributions to the subject of minimum temperature forecasting that appear later.

Figure 14 gives the parabola for November for 20 years. Figure 15 shows the data for December for 21 years, with the line computed from the November equation. This shows that these two months can be grouped together in making the calculations.

Figure 16 gives the data for November and December when the evening dew point was below 45°; figure 17 includes the nights when the dew point was between 45° and 54°, inclusive; and figure 18 when the dew point was above 54°. The resulting curves, while having a different shape, fit the data little, if any, better than the curves on figures 14 and 15.

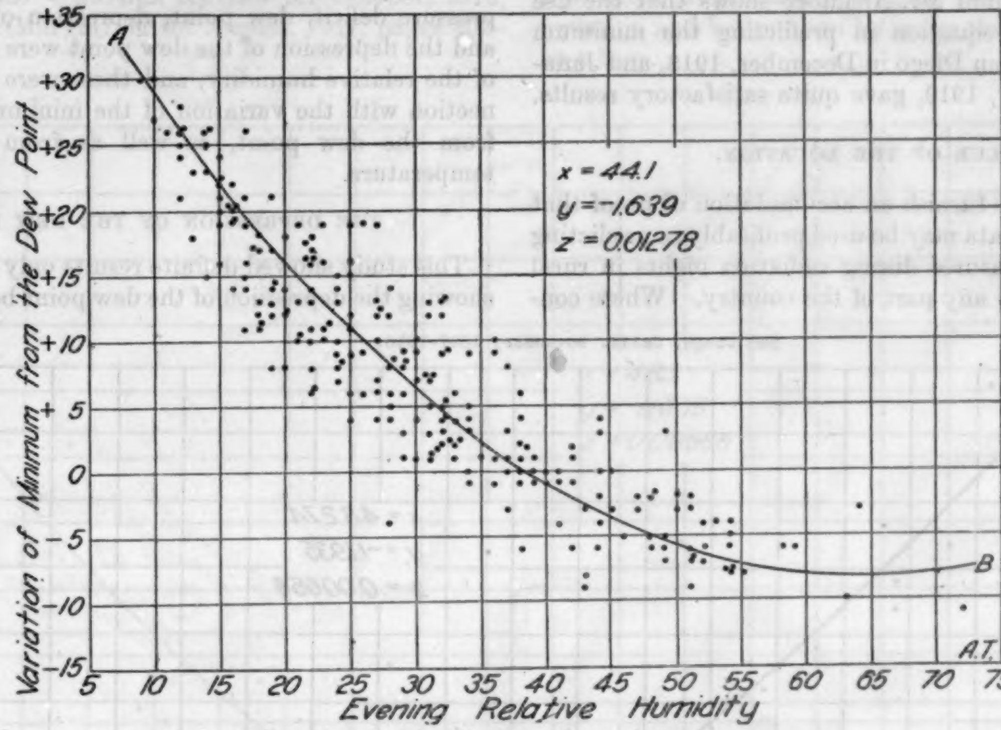

FIG. 12.—Phoenix, Ariz., July, 1916, to June, 1917. Ground exposure.

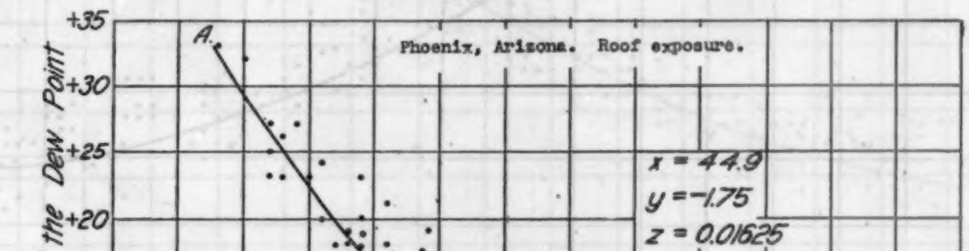

FIG. 13.—Phoenix, Ariz., November to March, 1914-1916. Roof exposure.

A study of the data shows that the values of the factors and the resulting curves vary with different dew points, hence the charts in figures 16, 17, and 18 were constructed.

The values of the unknown factors in the parabolic equation for January, February, and March at San Diego are as follows:

January, x = 38.394, y = −0.883, z = 0.00433; February, x = 38.0, y = −0.9167, z = 0.005. The position of the curves indicates that these months, and also March, can be grouped together with very satisfactory results.

A late report from Mr. Alciatore shows that the use of the parabolic equation in predicting the minimum temperatures at San Diego in December, 1918, and January and February, 1919, gave quite satisfactory results.

VALUE OF THE EQUATION.

All these figures furnish an accumulation of proof that the hygrometric data may be used profitably in predicting minimum temperatures during radiation nights in rural districts in almost any part of the country. Where considerable data are available, various local officials should chart them and calculate the curves as an aid in forecasting.

An inspection of the preceding figures shows quite a similarity in some of the curves, and seems to indicate that the equations and factors determined for one place can be used at any other place with a similar climate and topographic surroundings. It is suggested that at stations where only a small number of observations have been made the available data should be charted, an inspection made to see which chart it is probably nearest like, and then those factors used in making the estimate of the minimum temperature.

OTHER HYGROMETRIC FACTORS.

An exhaustive study was made by the writer to see whether better results could be obtained by using some other hygrometric factors. The vapor pressure, vapor pressure deficit, dew point, depression of the wet bulb, and the depression of the dew point were all used instead of the relative humidity, and these were charted in connection with the variation of the minimum temperature from the dew point, as well as from the wet bulb temperature.

THE DEPRESSION OF THE DEW POINT.

This study showed definite results only when the factor showing the depression of the dew point below the current temperature was used in place of the relative humidity, and was compared with the variation of the minimum temperature from the dew point.

The results from this correlation were so promising, however, that it is considered wise to submit some charts and calculations of these data, with the hope that they will prove helpful to local forecasters.

El Paso, Tex.—Figure 19 shows a dot chart for the depression of the dew point and variation of the minimum temperature from the dew point on radiation nights at El Paso, Tex., for March, April, and May, 1916 and 1917. The line *A B* was calculated by the equation

$$y=a+bR$$

San Diego, Calif. November, 1897-1916.

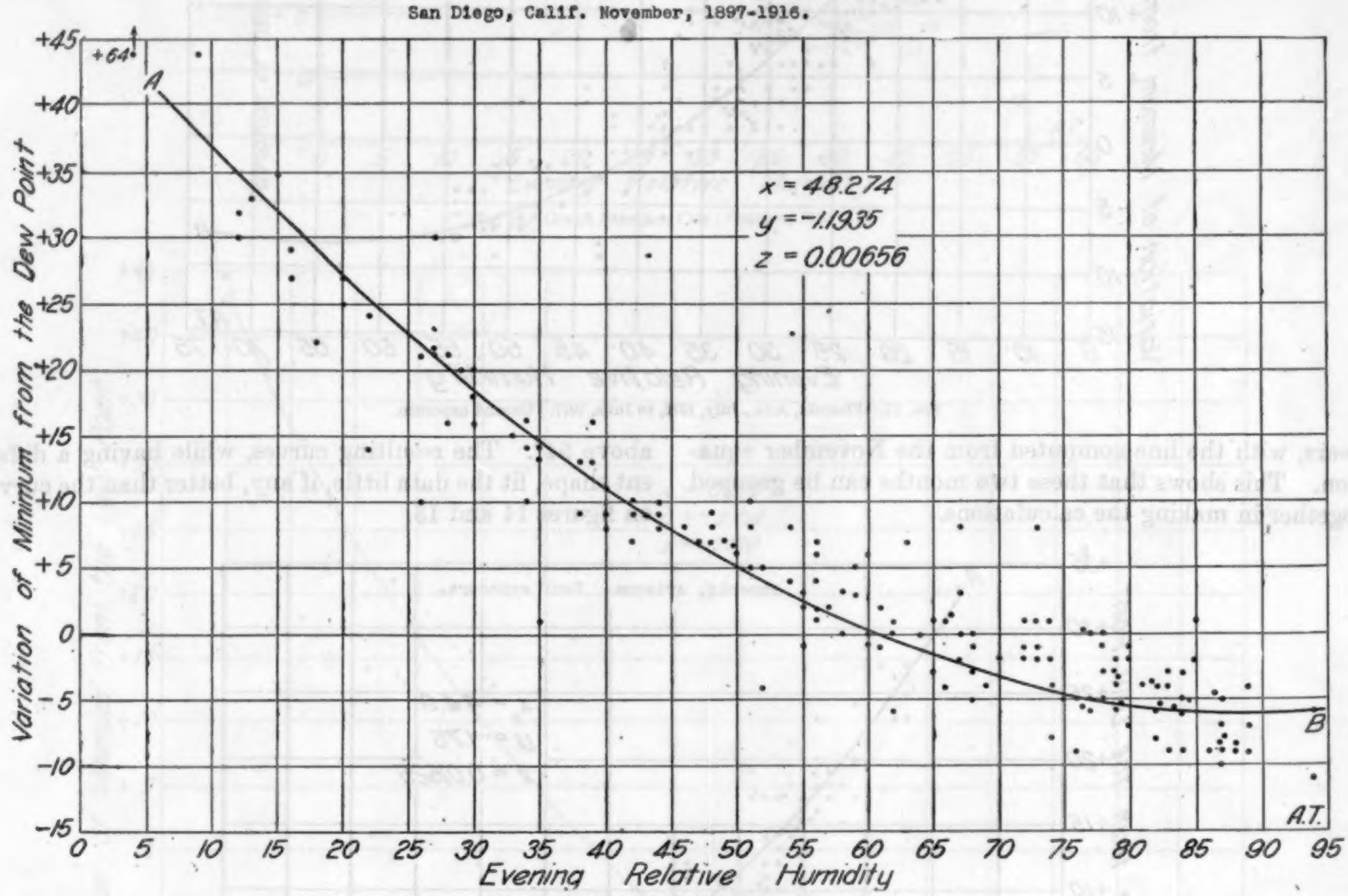

FIG. 14.—San Diego, Calif., November, 1897-1916.

in which R is the depression of the dew point and y the variation of the minimum from the dew point. The unknown factors a and b were found to equal -18.25 and 0.88, respectively. For an explanation of this method see the MONTHLY WEATHER REVIEW for October, 1916, pages 551–569 (Marvin), or for August, 1917, pages 402–407 (Smith).

depression of the dew point as a base, were found to be: $x=-3.0$, $y=0.175$, $z=0.0053$. In this calculation $b=$ the depression of the dew point and $c=$ the square of this depression in the equation $v=x+by+cz$. This parabolic line fitted the data better than from the straight-line equation and better than by using the relative humidity as a base.

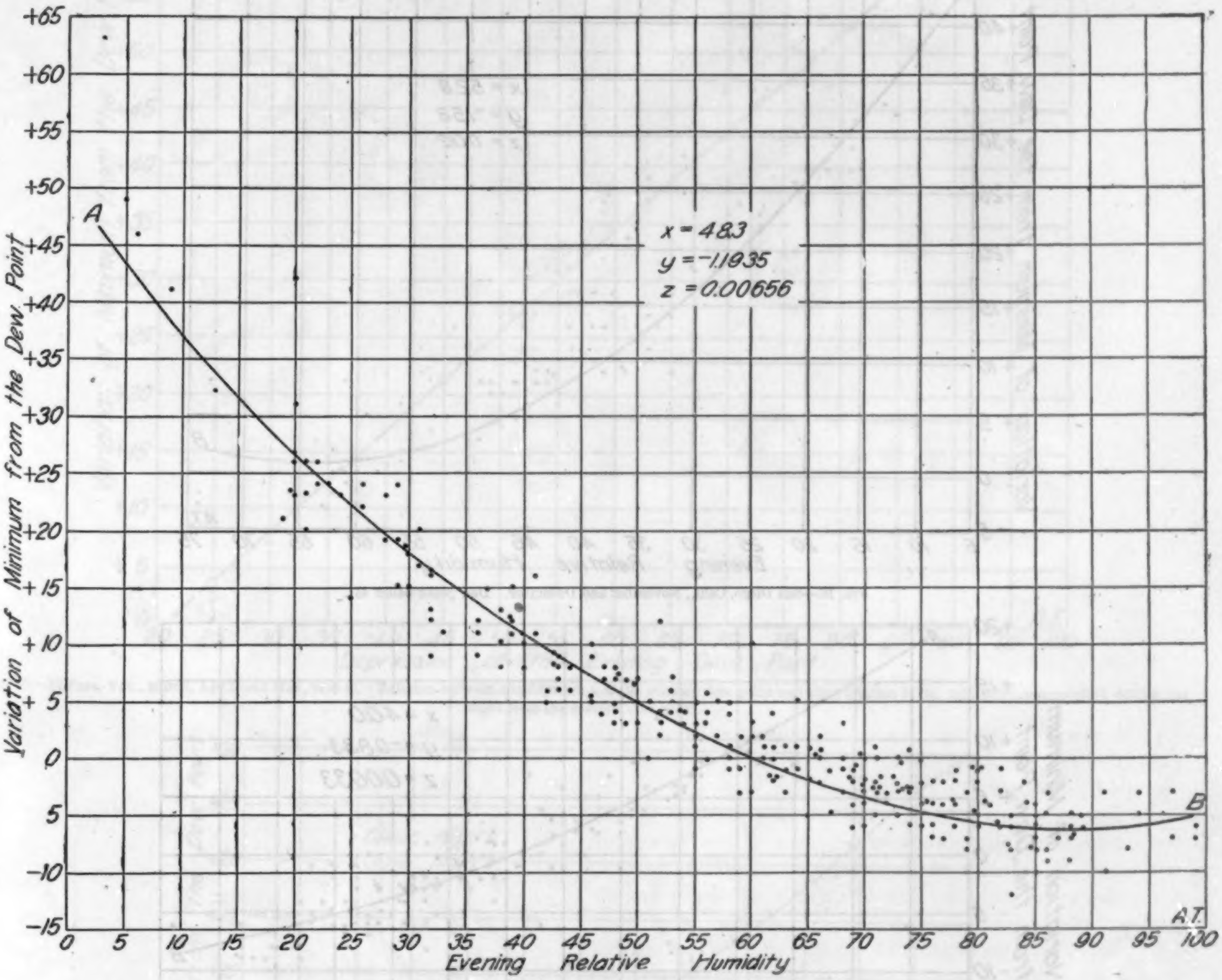

FIG. 15.—San Diego, Calif., December, 1896-1916.

As compared with figure 2, it will be seen at once that a straight line fits the data in figure 19 fully as well as any curve and that the dots are all surprisingly close to the calculated line A B. The dots for the different months all intermingle, showing that the hygrometric observation can be taken at any convenient hour in the early evening.

Agricultural College, N. Mex.—The values of the unknown quantities for March, April, and May, using the

Boise, Idaho.—In figure 20 the data for all nights from April 1 to June 15, 1918, were used. It was evident at once that a straight line was not the line of nearest fit, as in figure 19, hence the parabolic line A B was calculated. This fits the radiation nights quite well and all nights fairly so.

Corresponding charts using the depression of the dew point as a base were made for other places with fairly

good results. Without reproducing the charts, some of the values are:

Equation $y = a + bR$.

Lansing, Mich., $a = -11.2$, $b = 0.727$.

Grand Junction, $a = -7.01$, $b = 0.53$.

Equation $v = x + by + cz$.

Modena, Utah, all nights, $x = -7.3$, $y = 0.18$, $z = 0.0057$.

Montrose, Colo., $x = -22.0$, $y = 0.383$, $z = 0.01167$.

Phoenix, Ariz., ground exposure, $x = -12.4$, $y = 0.283$, $z = 0.00567$.

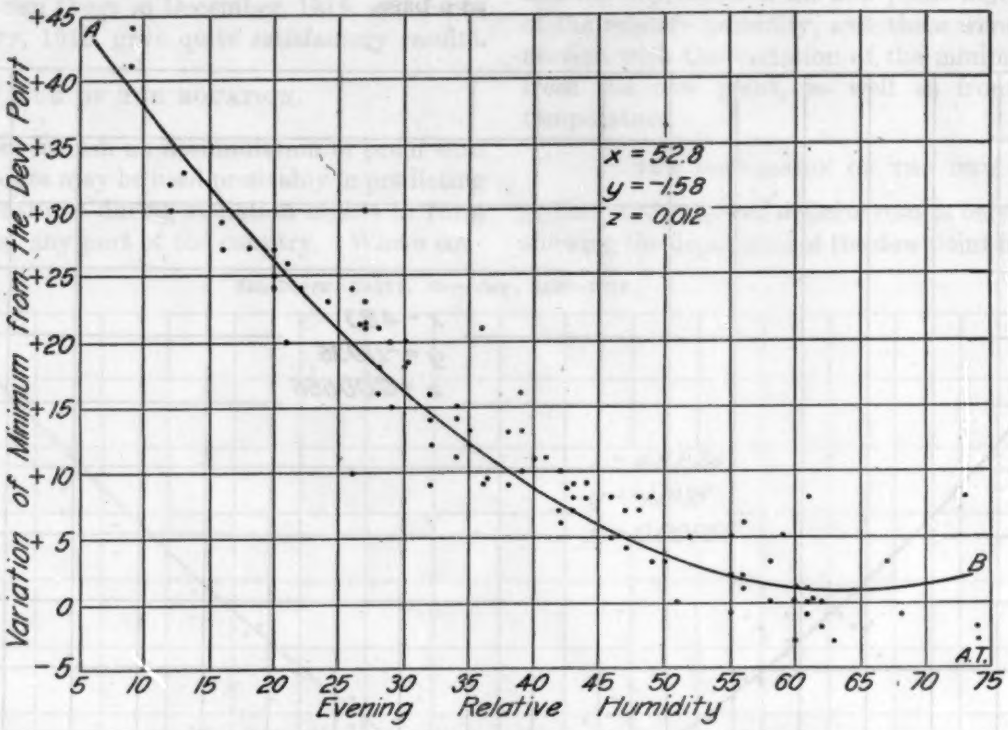

FIG. 16.—San Diego, Calif., November and December. Dew point below 45°.

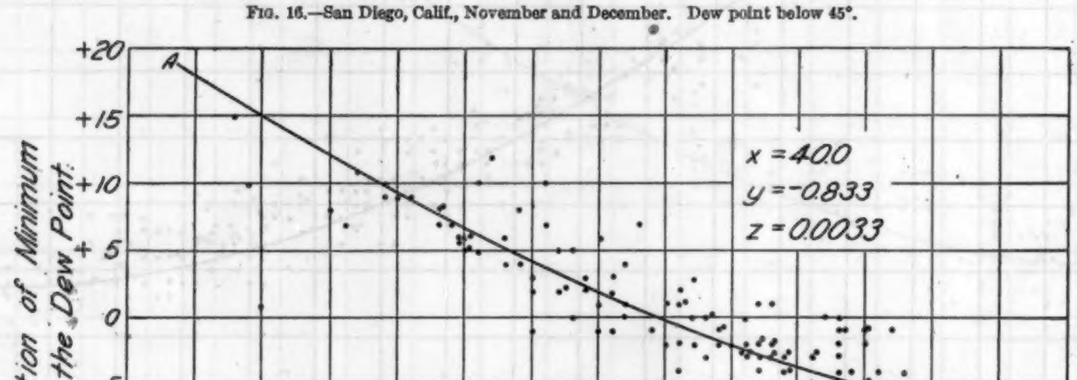

FIG. 17.—San Diego, Calif., November and December. Dew point between 45° and 54°.

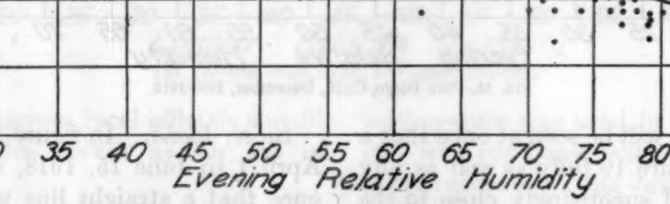

FIG. 18.—San Diego, Calif., November and December. Dew point above 54°.

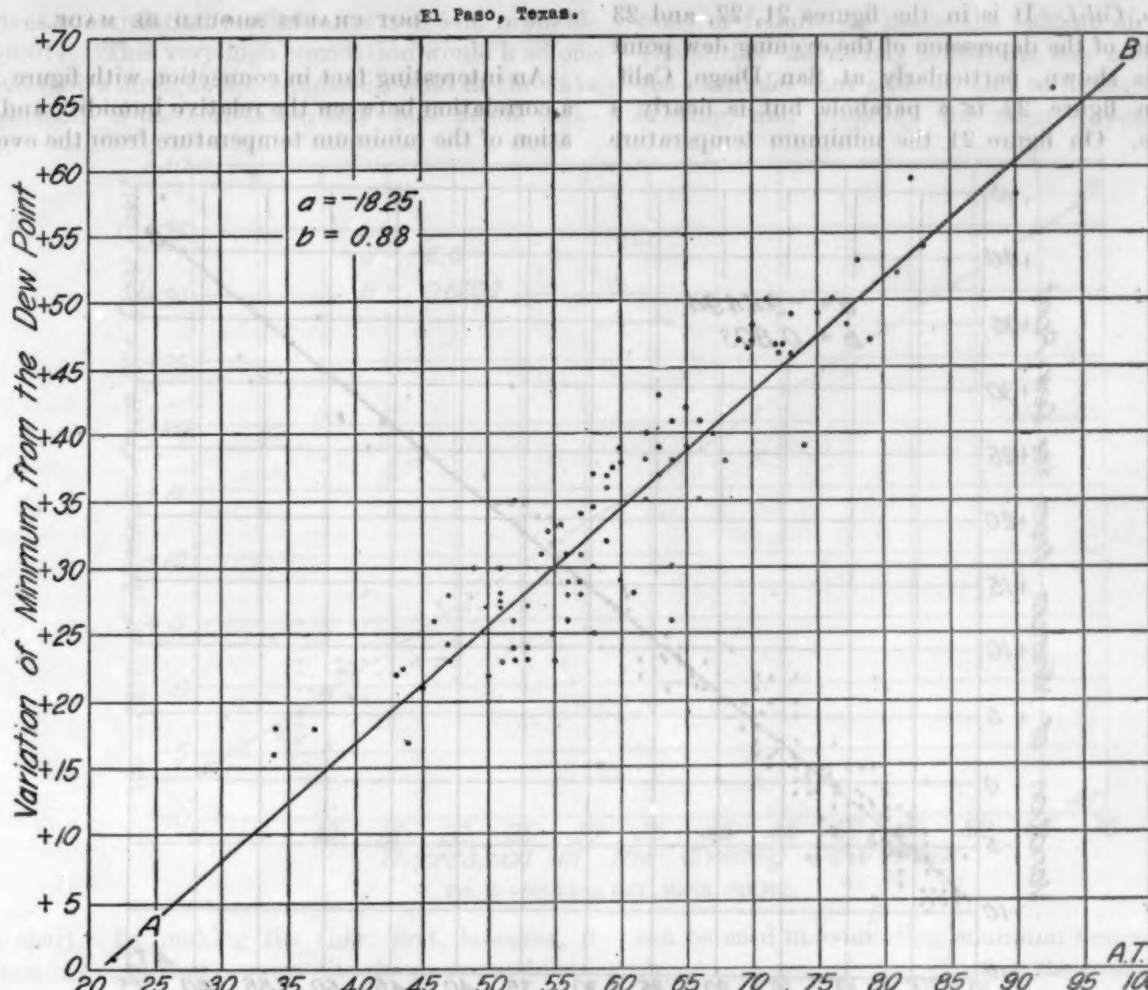

FIG. 19.—El Paso, Tex., March, April, and May, 1916-17. Relation between the depression of the evening dew point and the variation of the minimum temperature during the night from the evening dew point.

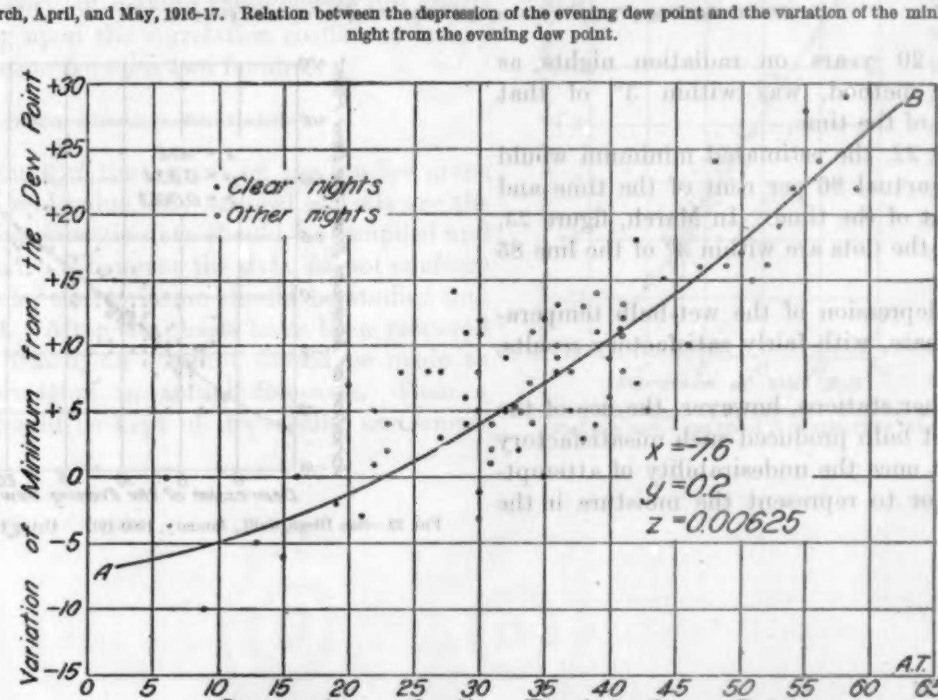

FIG. 20.—Boise, Idaho, April 1 to June 15, 1918. All nights, lawn exposure.

San Diego, Calif.—It is in the figures 21, 22, and 23 that the value of the depression of the evening dew point as a base is shown, particularly at San Diego, Calif. The line on figure 22 is a parabola but is nearly a straight line. On figure 21 the minimum temperature

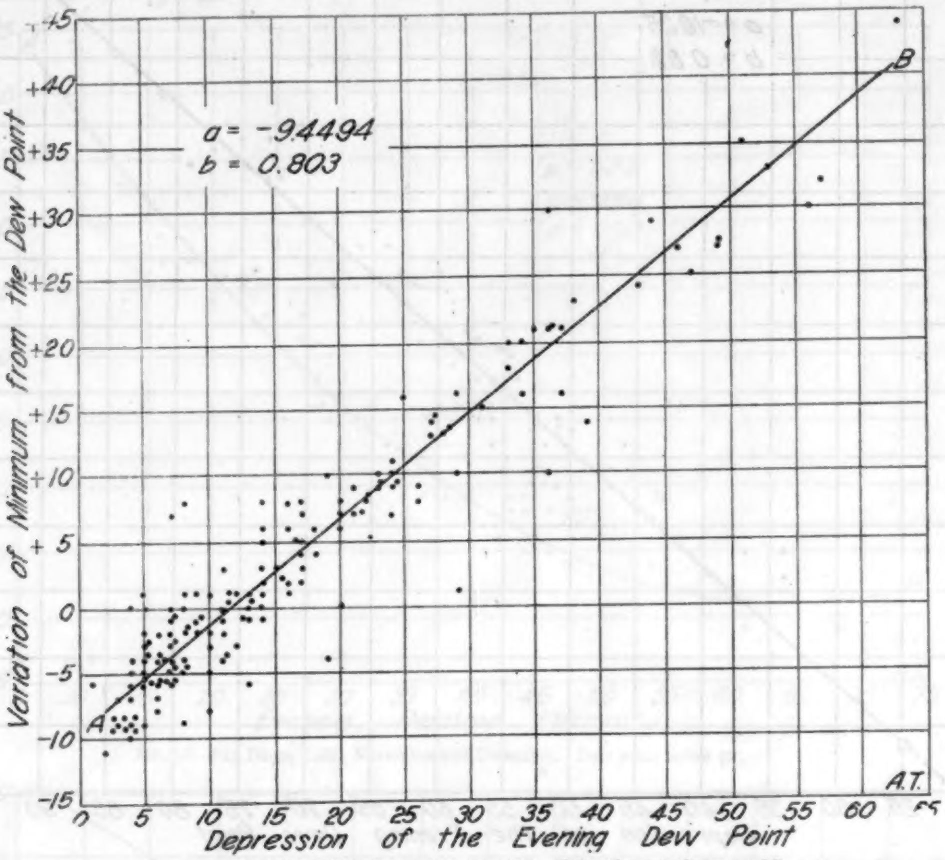

FIG. 21.—San Diego, Calif., November, 1897-1916. Using the equation $y=a+bR$.

for November for 20 years on radiation nights, as calculated by this method, was within 3° of that recorded 87 per cent of the time.

In January, figure 22, the estimated minimum would be within 3° of the actual 86 per cent of the time and within 4° 95 per cent of the time. In March, figure 23, for a shorter period, the dots are within 3° of the line 85 per cent of the time.

In figure 24 the depression of the wet-bulb temperature was used as a base, with fairly satisfactory results, at San Diego.

At some of the other stations, however, the use of the depression of the wet bulb produced such unsatisfactory results as to show at once the undesirability of attempting to use this factor to represent the moisture in the atmosphere.

DOT CHARTS SHOULD BE MADE.

An interesting fact in connection with figure 14 is that a correlation between the relative humidity and the variation of the minimum temperature from the evening dew

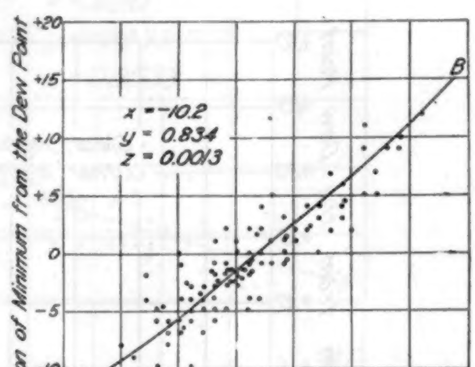

FIG. 22.—San Diego, Calif., January, 1900-1917. Using the equation $v=x+by+cz$.

point gives a correlation coefficient of −0.846, probable error ±0.014. This very high correlation would lead one to believe that a straight-line equation would fit the data nearly perfectly if the correlation was made before making the chart. By making the chart first, however, it will be seen at once that a curve fits the data much better than a straight line. This emphasizes the importance, and almost necessity, of making these simple dot charts before depending upon the correlation coefficient in any study of the relation between two factors.

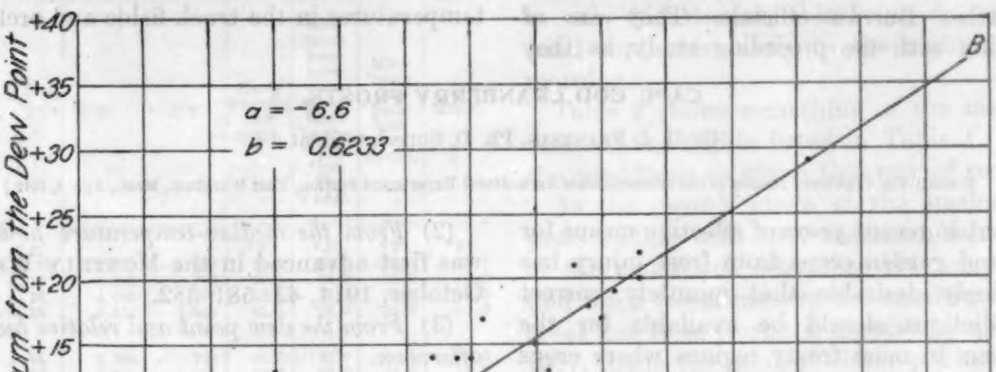

FIG. 23.—San Diego, Calif., March, 1913-1917.

DATA SHOULD BE USED.

The large amount of time spent on the studies given above will be of real value only as local officials use the information. Hygrometric data should be compiled and the method tested. Whenever the data do not conform to the general rule, the variation should be studied and the reason found. After the charts have been prepared and the curves drawn, an attempt should be made to utilize the information in actual forecasts. Then a careful record should be kept of the results, and variations or failures be made the subject of further study. The author has merely shown the way and given numerous examples that seem to him to demonstrate that the evening, and probably the noon, psychrometric data can be used in estimating minimum temperatures during the coming night, when radiation conditions prevail. At other times the weather map must be the sole guide. At the same time it is recognized that no rules or formulae can be used blindly. The weather maps must be studied also, and types determined under which the formulae may be used, or under which they must be modified.

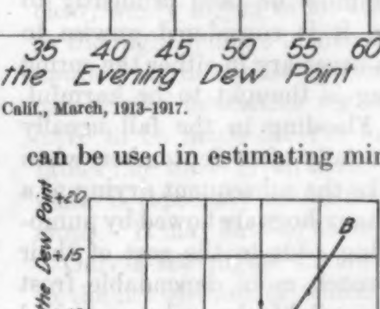

FIG. 24.—San Diego, Calif., January. The depression of the wet bulb temperature used as a base. The line A B calculated by the straight line equation $y=a+bR$.

SUPPLEMENT NO. 16.

FORECASTING MINIMUM TEMPERATURES.

By others.

The following are from letters, reports, or articles by various Weather Bureau officials. They are of value in connection with the preceding study, as they relate to actual experiences in predicting minimum temperatures in the truck fields and orchards.

CAPE COD CRANBERRY FROSTS.

By H. J. Franklin, Ph. D, Superintendent.

[Dated: The Cranberry Station of the Massachusetts Agricultural Experiment Station, East Wareham, Mass., Apr. 4, 1919.]

The development in recent years of effective means for protecting fruit and garden crops from frost injury has made it increasingly desirable that minutely correct temperature predictions should be available for the guidance of growers in most frosty regions where crops liable to such injury are raised. Profitable growing of some crops in sections where they usually are exposed to harmful frosts only a few times each year often depends largely on the economical use of heaters and this can be had only when the damaging temperatures are very exactly foretold.

Most cranberry growers can save their crops from frost by flooding. With many, however, water supplies are lacking or are limited and must be used prudently to meet all needs. Moreover, it is considered unwise to flood the vines more than is necessary in either the spring or the fall, as such flooding is thought to be harmful, especially if done often. Flooding in the fall usually interferes with picking, especially after September, when the lower temperatures make the subsequent drying of a bog a slow process. Also, many bogs are flowed by pumping, and every extra flooding adds to the cost of their care. For these reasons, much more dependable frost forecasts than have been available have been desired widely in all the main cranberry-growing regions.

General predictions of light or heavy frosts have been made from the morning weather map and distributed by the Weather Bureau for several years. These are often quite accurate and have value, but as they are made 15 to 21 hours before the lowest temperatures occur, and as unforeseen changes often develop in this time, they sometimes greatly mislead cranberry growers.

The first methods seeming to promise accuracy in computing minimum temperatures from local data were published recently [1] by Prof. J. Warren Smith, of the Weather Bureau. His methods, based on records made in Ohio, were all advanced as being useful on clear, still nights. He states that they are not of use "on cloudy or stormy nights or when strong winds prevail." The following are his three methods:

(1) *By the usual or average fall in temperature on clear, still afternoons and evenings after the maximum temperature of the day is known.*

(2) *From the median-temperature hour.*—This method was first advanced in the Monthly Weather Review, October, 1914, **42:** 581–582.

(3) *From the dew point and relative humidity in the late afternoon.*

One wishing to learn these methods should see Prof. Smith's papers. The first two seem too inaccurate to use on the Cape. The third, however, may be useful as it often seems to give some idea of the coming minimum temperature earlier in the evening than any other method. The writer has applied this method to all the still clear nights in which frost conditions existed and sufficiently complete records of which he kept in the years 1913 to 1917, inclusive. There were 20 such nights.

Prof. Smith,[2] in his third method, used a linear equation developed by the method of least squares. This method, explained in the Monthly Weather Review,[3] is used in Table 1 to determine the relation between the evening relative humidity and the minimum night temperature. In explanation of this table, therefore, we only need to repeat the formulae for getting the values of a and b in the equation $Y = a + bR$.

$$b = \frac{n\,(\Sigma RY) - (\Sigma R)\,(\Sigma Y)}{n\,(\Sigma R^2) - (\Sigma R)^2} = -0.176$$

$$a = \frac{\Sigma Y - b\,(\Sigma R)}{n} = -3.035$$

Therefore, for the station bog at East Wareham,

$$Y = a + bR = -3.035 - 0.176\,R$$

R being the evening relative humidity and Y the departure of the minimum temperature from the dew point, we have only to insert the value of R to compute that for Y which thus becomes the probable departure of the minimum to be deducted from the evening dew point on clear, still nights. To illustrate, let us substitute for R the relative humidity recorded in the evening of September 22, 1915, given in Table 1. The formula thus becomes, $Y = -3.035 - 0.176 \times 56 = -12.89$. This, taken from the dew point, 36° F., recorded in the evening of the date considered, leaves 23.1° F. as the minimum computed for the next morning. The temperature actually recorded was 22.5° F.

[1] Smith, J. Warren, Predicting Minimum Temperatures, Monthly Weather Review, August, 1917, **45:** 402–407.

(See the first paper in this Supplement showing the necessity of using the equation for the parabola instead of the straight line equation, in some places.—J. W. S.)

[2] Op. cit., p. 405.

[3] Marvin, C. F., Monthly Weather Review, October, 1916, **44:** 551–569.

TABLE 1.—*Evening relative humidity, R, and variation of the minimum temperature of the next morning from the evening dew point, Y, at the cranberry station for the dates in 1913 to 1917, inclusive, for which full records were kept and on which conditions favored radiation, together with the evening dew points and the computed and actual minimum temperatures.*

Dates.	R	Y	R^2	RY	Early evening dew point.	Minimum temperature calculated by the equation $Y=a+bR$.	Minimum temperature recorded.	Error.
1913.	*Per ct.*	°*F.*			°*F.*	°*F.*	°*F.*	°*F.*
May 26	55	$-9\frac{1}{2}$	3,025	-522	43.0	30.3	33.5	-3.2
Sept. 10	65	-12	4,225	-780	40.5	26.0	28.0	-2.0
14	67	-16	4,489	$-1,072$	43.0	28.2	27.0	$+1.2$
15	68	-16	4,624	$-1,088$	41.0	26.0	25.0	$+1.0$
1914.								
June 2	57	-14	3,249	-789	40.0	32.9	32.0	$+0.9$
Sept. 10	75	-17	5,625	$-1,275$	45.0	28.8	28.0	$+0.8$
11	76	-17	5,776	$-1,292$	46.0	29.6	29.0	$+0.6$
12	73	-22	5,329	$-1,606$	48.5	32.6	26.5	$+6.1$
1915.								
Sept. 22	56	$-13\frac{1}{2}$	3,136	-756	36.0	23.1	22.5	$+0.6$
30	90	-21	8,100	$-1,890$	47.0	28.1	26.0	$+2.0$
Oct. 9	96	-21	9,216	$-2,016$	45.0	25.1	24.0	$+1.1$
10	79	-18	6,241	$-1,422$	40.0	23.1	22.0	$+1.1$
1916.								
Sept. 11	75	$-16\frac{1}{2}$	5,625	$-1,238$	44.0	27.8	27.5	$+0.3$
17	76	-17	5,776	$-1,292$	48.5	32.1	31.5	$+0.6$
Oct. 1[1]	82	$-13\frac{1}{2}$	6,724	$-1,107$	40.0	22.5	26.5	-4.0
2	83	$-16\frac{1}{2}$	6,889	$-1,370$	43.0	25.4	26.5	-1.1
1917.								
Sept. 8	83	$-16\frac{1}{2}$	6,889	$-1,370$	48.0	30.4	31.5	-1.1
11	80	-18	6,400	$-1,440$	44.0	26.9	26.0	$+0.9$
22[1]	90	-15	8,100	$-1,350$	47.0	28.1	32.0	-3.9
Oct. 16	70	-14	4,900	-980	40.0	24.6	26.0	-1.4
Sums ($n=20$)	1,496 $=\Sigma R$	-324 $=\Sigma Y$	114,338 $=\Sigma R^2$	$-24,664$ $=\Sigma RY$	....	....	....	....

[1] Strong breeze from 10 p. m. on.

The relative humidities were taken in the instrument shelter, about 18 feet higher than the bog. The computation might be more accurate if it were based on the humidities at the bog level.

TABLE 2.—*Cranberry station barometer and anemometer records for the nights considered in Table 1.*

Date.	Wind velocity.[1]			Barometer record.			
	At 6 p. m.	At 8 p. m.	Average 12 to 6 a. m.	At 4 p. m.	At 8 p. m.	At 12 m.	At 6 a. m.
1913.	*Mis./hr.*	*Mis./hr.*	*Mis./hr.*	*Inches.*	*Inches.*	*Inches.*	*Inches.*
May 26	$2\frac{3}{4}$	$1\frac{3}{5}$	2	30.03	30.09	30.14	30.19
Sept. 10	1	$\frac{4}{7}$	$\frac{4}{5}$	....	30.41	30.40	30.31
14	$1\frac{1}{2}$	1	$3\frac{1}{5}$	30.32	30.42	30.50	30.59
15	$\frac{1}{2}$	$\frac{1}{2}$	1	30.57	30.62	30.65	30.67
1914.							
June 2	$2\frac{7}{8}$	$2\frac{7}{8}$	$2\frac{5}{8}$	30.05	30.10	30.13	30.12
Sept. 10	$1\frac{1}{2}$	$1\frac{4}{5}$	3	30.19	30.21	30.22	30.20
11	5	$2\frac{5}{8}$	4	30.17	30.21	30.22	30.25
12	3	$1\frac{1}{11}$	3	30.29	30.35	30.36	30.42
1915.							
Sept. 22	$2\frac{5}{8}$	4	$2\frac{1}{2}$	30.24	30.36	30.40	30.50
30	2	1	$2\frac{3}{4}$	30.30	30.31	30.32	30.33
Oct. 9	$\frac{4}{5}$	$1\frac{1}{2}$	$3\frac{4}{5}$	30.17	30.20	30.25	30.31
10	$\frac{4}{5}$	3	$3\frac{1}{2}$	30.37	30.44	30.50	30.57
1916.							
Sept. 11	3	2	$1\frac{1}{6}$	30.47	30.46	30.45	30.45
17	2	$1\frac{1}{6}$	$\frac{4}{5}$	30.25	30.25	30.24	30.22
Oct. 1	$2\frac{1}{2}$	$3\frac{1}{3}$	$4\frac{1}{5}$	30.40	30.43	30.44	30.45
2	2	2	$1\frac{1}{3}$	30.34	30.31	30.29	30.27
1917.							
Sept. 8	$3\frac{1}{3}$	3	$2\frac{1}{3}$	30.11	30.14	30.13	30.14
11	2	4	$1\frac{3}{5}$	30.16	30.21	30.25	30.30
22	$2\frac{1}{3}$	2	8	30.16	30.26	30.35	30.42
Oct. 16	$1\frac{1}{3}$	2	$4\frac{3}{5}$	30.00	30.07	30.14	30.24

[1] The cups of the station anemometer are about 48 feet higher than the bog level.

The last three columns of Table 1 show the results of applying the equation $Y=a+bR$ to the records of the nights listed. The computed temperature in the 20 cases included was within 1° of that recorded 8 times and within 2°, 16 times, the error being more than 3° in only 3 instances, this being due twice to a strong wind that arose early in the night and kept up until morning.

Table 2 shows something of the meteorological character of the nights listed in Table 1, giving an idea of the conditions to which this way of reckoning applies.

As the records made at the station during the five years ending with 1917 seemed a fair basis for a study of the conditions attending low temperatures on Cape Cod when frosts menace the cranberry bogs, and as the great loss from frost the nights of September 10 and 11, 1917, made the need of closer predictions seem urgent, the writer gave most of the winter of 1917–18 and much of the fall of 1918 to a careful investigation in this connection. The result of this work was a new way to compute minimum temperatures any night in which anything like strictly anticyclonic conditions prevail. This method probably can be refined much more, but it is advanced as being already valuable in forecasting at East Wareham. It probably is nearly as reliable for clear, windy nights as for still ones, but much cloudiness in the night renders it inaccurate. The principles of the method are doubtless applicable elsewhere, but before it can be used in another region several years' records may have to be made for the locality from which to make tables like those given here. Its construction is likely to make it especially useful for forecasting for low-growing crops. It may have to be modified for orchard conditions.

Only a few nights that were not frosty were included in the list of those of which records were studied. Most of those in which the bog minimum failed to reach 35° F. were omitted. When the temperature does not fall to near this point, therefore, the method as here presented may prove somewhat unreliable.[4]

The main factors used in the new method follow:

"*Forecasting factor 1.*"—This factor is based on the relationship between the average 8 p. m.[5] shelter temperature and the average bog minimum temperature[6] as observed at the station at East Wareham on frosty nights in a period of five years. Table 3 gives the averages by years.

[4] In actual forecasting in 1918 this computation, while usually satisfactory, was sometimes much too low, the condition oftenest attending such error, aside from cloudiness, being a falling or stationary barometer from 4 to 8 p. m., with a southwest wind of 5 or more miles an hour at 8 p. m. While this condition raised the minimum at the station considerably, apparently by bringing in warm air from the waters of Buzzards Bay, the reckoning on several such nights was fairly correct for South Carver and Norton, these points being 8 to 10 miles farther inland.

[5] All hours given in this paper accord with 75th meridian time.

[6] The phrase "bog minimum temperature" used in this report means the minimum air temperature recorded by a Green thermometer at the tops of the cranberry vines. As the minimum temperature on a bog on cold nights usually varies several degrees, the thermometer always should be placed in the coldest convenient location.

TABLE 3.—*Shelter temperatures at 8 p. m. and bog minimum temperatures recorded at the station at East Wareham, Mass., on frosty nights in seasons of frost danger, 1913 to 1917, inclusive, averaged in comparison.*

Year.	Nights averaged.	Average of 8 p. m. shelter temperatures.	Average of bog minimum temperatures.
		°F.	°F.
1913	10	45⅞	27½
1914	12	50⅓	29¾
1915	8	46⅛	27
1916	3	46⅔	29⅓
1917	21	45¾	30⅓
Averages of the 54 nights		46⅞	29

The general average is 47° F. for 8 p. m. shelter temperatures and 29° F. for bog minimum temperatures.

"Forecasting factor 1" is obtained by either adding to or subtracting from 29° the difference, above or below, as the case may be, between 47° and the shelter temperature observed at 8 p. m.

Examples.—(*a*) If the shelter temperature at 8 p. m. is 54° F., then 7° is to be added to 29°, making "Forecasting factor 1" 36° F.

(*b*) If the 8 p. m. shelter temperature is 44° F., then 3° is to be subtracted from 29°, leaving 26° F. as "Forecasting factor 1."

"Forecasting factor 2."—This factor depends on the following:

(*a*) Dew point at 8 p. m.

(*b*) Atmospheric pressure at 8 p. m. and the amount of its increase from 4 to 8 p. m. (Table 4).

(*c*) Wind velocity at 8 p. m. (Table 5).

TABLE 4.—*Barometer correlation table for calculating "Forecasting factor 2" at the station bog, East Wareham, Mass.*

Reading of barometer at 8 p. m.	Reading No.	Rises of barometer from 4 to 8 p. m. and the corresponding multipliers for computing the number of degrees to be subtracted from the 8 p. m. dew point.				
		0.00 to 0.03.	0.03 to 0.06.	0.06 to 0.09.	0.09 to 0.12.	0.12 and more.
29.8 and below	1	0	1	2	3	4
29.8 to 29.9	2	½	1½	2½	3	3½
29.9 to 30	3	1	1⅔	2⅓	3	3⅓
30 to 30.1	4	1½	1¾	2¼	2¾	3
30.1 to 30.2	5	1⅕	1⅗	2	2⅖	2⅘
30.2 to 30.3	6	1⅓	1½	1⅔	2	2½
30.3 to 30.4	7	1⅐	$1\frac{4}{7}$	$1\frac{5}{7}$	$1\frac{6}{7}$	$2\frac{2}{7}$
30.4 and above	8	1¼	1⅜	1⅝	1⅞	2

The table gives a number for each of eight readings of the barometer at 8 p. m., these covering its common movements. The table is based also on the rise of the barometer from 4 to 8 p. m., 5 amounts of which are used. For each reading number of the barometer a multiplier is given for each amount of its rise. These multipliers present complete and fairly even gradations both vertically and horizontally. They were determined from what occurred at the station bog on cold nights in the frost periods of 1913 to 1917, inclusive. They are not means, for not enough records have accumulated to produce them all satisfactorily by averaging. How they were obtained is told below. Facility of the table's use as well as its accuracy was considered in its preparation, the fractions of the multipliers being made to conform to the reading numbers so as to make the products integers in all cases.

To use Table 4, multiply the proper reading number by its multiplier corresponding to the amount of the barometer rise observed in the evening and deduct the product from the 8 p. m. dew point. The remainder is termed "Forecasting factor 2." For example:

1. If the barometer stands at 30.23 inches at 8 p. m., and has risen 0.07 inch since 4 p. m., the dew point being 47° F. at 8 p. m., multiply the reading number 6 by the multiplier 1⅔ and subtract the product (=10°) from the dew point (47°), leaving 37° as "Forecasting factor 2."

2. If the barometer stands at 30.10 inches at 8 p. m. and has risen 0.05 inch since 4 p. m., the dew point being 49° F. at 8 p. m., multiply 2 reading numbers by their multipliers and average the products as follows:

Reading number.	Multiplier.	Product.
4	1¾	7°
5	1⅗	8°

Deduct the average of the two products (=7½°) from 49° (the dew point), leaving 41½° as "Forecasting factor 2."

3. If the barometer stands at 30.23 inches at 8 p. m. and has risen 0.09 inch since 4 p. m., the dew point being 50° F. at 8 p. m., multiply the reading number 6 by the multiplier 1⅔ (product =10°) and the multiplier 2 (product =12°) and average the products (=11°). Subtract 11° from 50° (the dew point), leaving 39° as "Forecasting factor 2."

4. If the barometer stands at 30.20 at 8 p. m. and has risen 0.06 since 4 p. m., the dew point being 45° F. at 8 p. m., multiply each of two different reading numbers by two different multipliers and average the four products, as follows:

Reading number.	Multiplier.	Product.
5	1⅗	8°
5	2	10°
6	1½	9°
6	1⅔	10°

Deduct the average of the four products (=9¼°) from 45° (the dew point), leaving 35¾° as "Forecasting factor 2."

To compute the bog minimum temperature at the station on windy nights average "Forecasting factor 1" and "Forecasting factor 2."—On still nights (with a wind velocity of 6 or less miles an hour at 8 p. m.) the following table should be used in connection with the calculation described above.

TABLE 5.—*Air-drainage table.*

Wind velocity at 8 p. m.	Subtract from "Forecasting factor 2."	Wind velocity at 8 p. m.	Subtract from "Forecasting factor 2."
Mis. hr.	° *F.*	*Mis. hr.*	° *F.*
6	½	2⅔	7
5	1	2⅓	7½
4½	2	2	8
4	3	1⅔	8½
3⅔	4	1⅓	9
3⅓	5	1 and less	9½
3	6		

With this table the method of computing is not altered except that the proper subtraction from "Forecasting factor 2" for the wind velocity observed at 8 p. m. is made before that factor is averaged with "Forecasting factor 1." As stated in the discussion of wind velocities below, the 8 p. m. velocity as applied in Table 5 is to be corrected under some conditions.

The following corrections to the reckoning as thus far described should be noted in their order:

A. If the sky is mostly overcast at 8 p. m., 12° should be subtracted from "Forecasting factor 1" before it is averaged with "Forecasting factor 2."

B. If half of the shelter maximum temperature is less than the average of the two "Forecasting factors," it should be substituted for that average as the prediction for the night. If it has been cloudy all day, 12° should be added to the maximum before it is halved.

With the writer's records for 1913 to 1918, inclusive, this correction improved the computation 18 of the 27 times it was applied, the improvement often amounting to several degrees. It failed to change it twice and made it less accurate by half a degree three times, by a degree twice, and by 1¾° twice.

C. By a thorough investigation of the morning weather maps of the Weather Bureau, in connection with the study of his local records, the writer has succeeded in defining eight types of pressure distribution which seem to have special significance in local forecasting of bog minima on the Cape.

I. *Safe types* (with which the bog minimum is usually higher than the computation):

1. With a LOW central off or over the Atlantic coast between South Carolina and Boston.

Examples.—June 12, 1913; September 16 and October 11, 1917; October 7 and 18, 1918.

2. With (*a*) a HIGH central over New York, Pennsylvania, southern Ontario, the southern peninsula of Michigan, Indiana, Ohio, or the Virginias, or to the south thereof; (*b*) a HIGH central over the Canadian northwest or over Washington, northern Idaho, or western Montana; (*c*) a strong LOW central over Utah, Wyoming, Colorado, South Dakota, Nebraska, or western Kansas; (*d*) a LOW central over or near New Brunswick, or none.

Examples.—1916, May 19 and October 2 and 18; 1917, October 17; 1918, May 9 and 24, August 19, and September 23.

With this map, it usually clouds up in the night. The less the difference in pressure between the center of the eastern HIGH and the margin of the Gulf of Mexico, the safer this type seems.

II. *Dangerous types* (with which the temperature usually falls below the computation).[7]

1. With (*a*) a HIGH central near Sault Ste. Marie (not south of Sault Ste. Marie nor west of Port Arthur nor east of Parry Sound) and extending to North Carolina or Florida; (*b*) a LOW central over either New Brunswick or Nova Scotia or both; (*c*) no LOW central east of the Florida peninsula or over the Atlantic seaboard between Florida and Boston; (*d*) a LOW central over Kansas, Missouri, the northern part of the Gulf of Mexico, or some of the Southern States between Florida and New Mexico[8] or none; (*e*) no LOW central over North Dakota; (*f*) no HIGH central over the Canadian Northwest.

Examples.—1913, May 14 and 20; 1914, June 5 and September 8; 1915, May 19 and 28 and September 27, 28, 29, and 30; 1917, September 22; 1918, May 4, June 15 and 18, and September 10 and 24.

2. With (*a*) a HIGH central near (not south of) Stonecliffe, Ontario, and extending southward to the Gulf of Mexico; (*b*) no LOW central east of a straight line from Winnipeg to Fort Worth, except sometimes a weak one over New Brunswick or Nova Scotia.

Examples.—1914, September 12, 19, and 28; 1918, May 15 and August 27; 1919, May 6.

With this map, the bog minima thus far average about 1¼° below those computed. The calculation always should be corrected by subtracting this number.

3. With (*a*) a HIGH central over (not south of) New England, or over New England and New York, or just off the New England coast, and extending southwesterly to the Gulf of Mexico, the isobars between this HIGH and the western area of low pressure running from the north in a distinctly southwesterly direction to or beyond Tennessee before turning to the south or southeast, and the difference in pressure between the center of the HIGH and the northern margin of the Gulf of Mexico not less than 0.3 inch; (*b*) no LOW central east of the Mississippi River, except sometimes a weak one over Nova Scotia or New Brunswick,

Examples.—1914, September 14 and 15; 1916, September 11 and October 2;[9] 1918, May 16 and August 28

With this map, the reckonings so far average about 2° higher than the bog minima recorded. The computation always should be corrected by subtracting this error.

4. With (*a*) a strongly longitudinal HIGH running from between Winnipeg and Albany on the north to between New Mexico and the Carolina coast on the south, its

[7] The probable effect of any slight secondary LOW that the map may show should always be considered. The map for Oct. 22, 1917, shows such a LOW over Ontario and that for Oct. 16, 1918, one over Pennsylvania, New York, and Ontario.

[8] It is well to remember that the centers of LOWS do not, as a rule, cross isotherms but usually follow the general trend of the isothermal lines.

[9] The map on this date showed a peculiar combination of safe type 2 and dangerous type 3. The minimum temperature recorded was 1.2° higher than that computed.

center not west of a straight line from Port Arthur, Ontario, to Port Arthur, Tex., and not east of a line from the eastern margin of Georgian Bay (Parry Sound) to the southwestern corner of Georgia; (*b*) the pressure at the center of the HIGH not more than 0.2 inch higher than that at or opposite (in the same latitude as) Sault Ste. Marie; (*c*) a LOW central near or over New Brunswick; (*d*) a LOW central over Florida or none; (*e*) a LOW central over the Canadian Northwest; (*f*) no strong LOW central squarely over New England; (*g*) no LOW over the Atlantic seaboard between South Carolina and Boston; (*h*) no strong LOW central over Utah, Wyoming, Colorado, South Dakota, Nebraska, or western Kansas.

Examples.—1914, May 15 and September 26; 1915, September 22 and October 9; 1916, September 19; 1917, October 6; 1918, June 8, September 21, October 3, 14, and 21.

This map seems to be most certainly dangerous when the long axis of the approaching HIGH runs northeasterly and southwesterly.

5. With (*a*) most of the country under high pressure, the pressure growing constantly greater from the east westward and culminating in a HIGH center over either the Canadian northwest or the northwestern United States; (*b*) the isobars strongly longitudinal (i. e., running north and south) over the Middle West; (*c*) a LOW central near or over New Brunswick; (*d*) a LOW central over Florida or none; (*e*) no other considerable LOW present, except possibly on the Pacific coast.

Example.—September 29, 1918.

This type is a modification of type 4, a strong northwestern HIGH being superimposed on the eastern one.

6. With (*a*) a HIGH over New England or New York or both; (*b*) a second HIGH, usually as strong or stronger than the first, central over or to the north of Wisconsin, Iowa, Nebraska, Minnesota, or the Dakotas; (*c*) a moderate LOW over New Brunswick or Nova Scotia or none; (*d*) a LOW central somewhere in the southern two-thirds of the Middle West; (*e*) no LOW east of Florida or along the Atlantic seaboard between South Carolina and Boston.

Examples.—1913, May 8; 1914, September 11; 1915, May 29 and 30; 1918, October 23 and 24; 1919, May 19.

The cape winds are usually southerly, and therefore misleading, with this type. It is almost sure to be dangerous if the barometer rises at all from 4 to 8 p. m. The Middle West LOW presses against a HIGH north of it, partly divides it, and then sometimes dissipates. The pressure of this LOW seems to intensify the cold. With this type, 2° should be subtracted from the reckoning.

The calculation by the new method is usually too high when any of the six dangerous types of pressure distribution here described prevail. Under some conditions the error with the first, fourth, and fifth types is large. Table 6 is based on the local records and gives what seem proper corrections to the reckoning when the map shows any of these three types.[10]

TABLE 6.—*Corrections for dangerous map types 1, 4, and 5 when the barometer is 29.75 inches or above at 4 p. m.*

Rise of barometer from 4 to 8 p. m.	Pressure differences between center of most eastern HIGH[1] and center of northeastern LOW[2] of morning weather map and corresponding corrections to be subtracted from the computed bog minimum temperature.					
	0.3 and less.	0.3 to 0.4.	0.4 to 0.5.	0.5 to 0.6.	0.6 to 0.7.	0.7 to 0.8.
	°F.	°F.	°F.	°F.	°F.	°F.
0.04 to 0.06	1.0	1.0	0.5	0	0	0
0.06 to 0.08	2.0	2.0	1.5	1.0	0.5	0
0.08 to 0.10	3.5	3.0	2.5	2.0	1.0	0
0.10 to 0.12	4.5	4.0	3.5	2.5	1.5	0.5
0.12 and more	5.0	4.5	3.5	2.5	2.0	1.0

[1] With the fifth type the pressure at Sault Ste. Marie may be taken as representing the center of the HIGH.

[2] The form of the LOW should be noted. If the isobars are long and straight, suggesting that its center is so far out at sea that the map does not nearly show its full intensity, this should be carefully considered.

D. When, as on Sundays and holidays, the weather map is not available, one may be almost sure that the distribution of atmospheric pressure is dangerous if the temperature on the bog at the station at 7 or 8 p. m. is more than 15° below either the shelter temperature (17 feet 8 inches higher) or the dew point. When the temperature at the bog level is thus depressed in the evening, $2\frac{1}{2}$° should be deducted from the reckoning.

E. If the wind begins to blow from the south or southeast between 1 and 4 p. m. and continues to come steadily from either of those directions until 8 p. m., 7° should be added to the calculation. This allowance should not be made if the wind begins to blow from the south or southeast before 12:30 p. m.

F. Occasionally cold nights occur in which the temperature is kept several degrees above the computed minimum apparently by abnormal conditions of the upper atmosphere. Such nights are cloudless, but a layer of either warm or very humid air well up from the earth, without cloud formation, probably has an effect on temperatures similar to that of cloudiness. The writer knows no certain way to detect these conditions in windy weather, but with an average wind velocity of 4 miles or less per hour from 6 to 8 p. m. their presence is shown by the 8 p. m. bog temperature. In reckoning on such still nights, these conditions can be allowed for by determining the bog minimum by the following table:

TABLE 7.—*Calculation based on 8 p. m. bog temperature.*

Average wind velocity from 6 to 8 p. m. (miles per hour).	Factor.	Average wind velocity from 6 to 8 p. m. (miles per hour).	Factor.
1 and less	$4\frac{1}{2}$	$2\frac{1}{2}$ to 3	$3\frac{1}{4}$
1 to $1\frac{1}{2}$	4	3 to $3\frac{1}{2}$	3
$1\frac{1}{2}$ to 2	$3\frac{3}{4}$	$3\frac{1}{2}$ to 4	$2\frac{3}{4}$
2 to $2\frac{1}{2}$	$3\frac{1}{2}$		

[10] See "Weather Forecasting in the United States," Weather Bureau Bulletin No. 583, 1916, p. 208.

This table is based on the records of the cranberry station. To use it, multiply the wind velocity in miles (and fractions thereof) by the corresponding factor and subtract the product from the 8 p. m. bog temperature. *If the remainder is higher than the temperature otherwise calculated, it should be used as the forecast.* This computation should not be used, however, if there is much cloudiness at 8 p. m. or if the wind velocity is much greater at 8 p. m. than at 6 p. m.

G. The general climate seems to fix a point for each day in both the spring and the fall frost period below which the bog temperature at the observing location of the station at East Wareham can not go, even under extreme conditions. The writer calls this point the *potential minimum.* Space does not allow a full discussion of the studies made in this connection, but what results are important in forecasting are given here.

As the potential minimum is so seldom reached,[11] (it seems to have been quite or about reached at the station on only the following five nights since observing was begun there in the spring of 1911—Aug. 20–21, 1913, Sept. 22–23, 1915, Sept. 10–11, 1917, Nov. 2–3, 1917, June 20–21, 1918),[12] the writer has found it wise to establish a *forecasting potential* 2½° above the potential minimum for use in predicting. This "potential" for April 20 for the station bog thermometer location is 19° F. and rises at a uniform rate of about one-sixth of a degree a day from that date until nearly June 30, and then rises much more rapidly. The midsummer potential minimum seems to be 36° F.

The forecasting potential for August 15 is 33½° F. and falls at a uniform rate of a quarter of a degree a day from that date until November.

The following examples show how the potential for any date in the frost danger periods may be determined:

1. For May 20. This being 30 days later in the spring than April 20,

   $30 \times \frac{1}{6} = 5$.

   19° F. (the Apr. 20 potential) + 5° = 24° F. – the potential sought.

2. For September 10. This is 26 days later in the fall than August 15. Therefore,

   $26 \times \frac{1}{4} = 6\frac{1}{2}$.

   33½° F. (the Aug. 15 potential) – 6½° = 27° F. – the desired potential.

In the frost danger periods of the last eight years the station bog minimum has been within 2½° (above and below) of the forecasting potential 49 times, within 2° 32 times, within 1½° 26 times, within 1° 23 times, and within half a degree 12 times.

When the potential for any date is higher than the computed minimum, it should be used as the forecast.

The new way of calculating has been applied to the station records of the years 1913 to 1917, inclusive, where these are full enough to do so, and the computed temperature was within half a degree of that recorded 17 times, within 1° 27 times, within 1½° 36 times, within 2° 44 times, within 2½° 51 times, and within 3½° 52 times. On four of the five remaining nights peculiar conditions prevailed. Of the 57 nights, 27 were windy, the 8 p. m. wind velocity being 3 miles or more an hour. The other 30 were favorable for radiation, the 8 p. m. velocity being less than 3 miles. The highest 8 p. m. velocity was 20 miles and the lowest half a mile an hour. The highest average velocity from midnight to 6 a. m. was 12 miles and the lowest seven-tenths of a mile. The greatest rise of the barometer from any 4 p. m. to the following 6 a. m. was 0.66 inch and the greatest fall 0.18 inch. The greatest rise of the dew point from early evening to 8 o'clock the next morning was 10° F. and its greatest fall 11° F.

Actual predicting was done by the new method at 8 p. m. on 39 clear nights in 1918, the computed temperature being within half a degree of the recorded one five times, within 1° 13 times, within 1½° 18 times, within 2° 25 times, within 2½° 30 times, and within 3° 34 times.

Twenty-one of these 39 nights had a wind velocity of 3 miles or more an hour and the other 18 a velocity of less than 3 miles at 8 p. m. The highest 8 p. m. velocity was 15 miles and the lowest two-fifths of a mile. The highest average velocity from midnight to 6 a. m. was about 16 miles and the lowest 1 mile. The greatest rise of the barometer from any 4 p. m. to the next 6 a. m. was 0.31 and the greatest fall 0.13. The greatest rise of the dew point during the night was 11½° F. and its greatest fall 12°.

These studies of the records of 96 cold nights in the frost periods of six seasons seem ample to prove that the new method of calculating is reasonably reliable.

After careful study of the errors made, the writer thinks that, to reckon for entire safety at the station bog, 3° always should be subtracted from the computed minimum when the weather map shows any of the dangerous types of pressure distribution except the second or when the forecasting potential is used. Otherwise, only 1½° need be deducted.

The steps by which the new way of reckoning was built up were as follows:

1. *The determination of the average relationship of the 8 p. m. shelter temperature to the bog minimum.*—Table 3 shows how this was ascertained. "Forecasting factor 1" rests solely on this relation. The 8 p. m. temperature at the bog level was tried in this connection, but it gave far less correct calculations than that of the shelter.

The station shelter thermometer[13] is 17 feet 8 inches above and about 178 feet from the bog thermometer and about 8 feet below the crest of a near-by hill. As it

[11] In the frost danger seasons of the last eight years the station bog minimum has been within 1½° of the potential minimum 9 times, within 2° 14 times, and within 2½° 19 times. These approaches to the potential minimum usually have been associated with long dry spells. They are, therefore, especially dangerous, as they are so likely to come, sometimes in a series, when the water supplies for flooding are low. (See Cox, Henry J., Frost and Temperature Conditions in the Cranberry Marshes of Wisconsin, Weather Bureau Bulletin T, 1910, p. 114.)

[12] The bog temperature fell to the potential minimum the night of Apr. 22–23, 1919, and apparently did no harm on most exposed bogs, but it killed over half of the Early Black buds on a large bog in Norton, Mass. It did not hurt the Howes buds on that bog.

[13] This thermometer is 10½ feet from the ground.

seemed unlikely that this thermometer was placed accidently at an elevation to show 8 p. m. temperatures that would give the best results in computing, a special study about this was made in 1918. Four unsheltered thermometers were placed on poles several hundred feet apart, all at the same height as the shelter thermometer, and one was attached to the trunk of a pine 60 feet above the bog thermometer. Readings were taken as shown in Table 8.

TABLE 8.—*8 p. m. temperatures of frosty nights at different elevated locations near the station bog compared with each other and with the 8 p. m. bog temperature.*

Date.	Numbers and elevations above the bog thermometer of the various thermometers and the 8 p. m. readings taken.					Bog temperature at 8 p. m.	Wind velocity at 8 p. m. (miles per hour).
	No. 1.[1]	No. 2.[1]	No. 3.[1]	No. 4.[1]	No. 5.[2]		
	17′ 8″	17′ 8″	17′ 8″	17′ 8″	60′		
1918.	°F.	°F.	°F.	°F.	°F.	°F.	
June 19	50	49½	50	48½	51	43	5.0
20	44½	44	43	46	50½	30	1.0
23	51	51	50½	50½	51¾	50	8.6
Sept. 21	48½	48	......	48	50	......	2.4
22	48½	47	47	48	49	......	4.0
23	53¾	52	52½	53	53¾	......	4.7
24	46½	45	47	47	50¾	34	1.7
27	51	49¼	50	50	51	47½	6.0
Oct 1	30½	38¾	39	40½	44¾	27	2.7
4	50	47	49½	50¼	51	45	4.0
7	46	45½	46	44	47	......	8.5
8	36	35	35	36	38¾	24½	1.3
Average	47	46	46½	47	49	......	......

[1] These thermometers ranged from 16 inches (over high land) to 16 feet 8 inches (over low land) from the ground.
[2] Over high land and 43 feet 8 inches from the ground.

The readings in Table 8 show, first, that the difference in the 8 p. m. temperature between the 17 foot 8 inch and the 60 foot elevations is usually slight and is but moderate even when conditions favor air drainage most (e. g., June 20—this night was entirely clear, the average wind velocity from 7 to 8 p. m. being a little less than 1 mile an hour); and, second, that the difference in the 8 p. m. temperature between the bog level and the 17 foot 8 inch elevation is, proportionally to the difference in altitude, almost always from four to eight times as great as that between the 17 foot 8 inch and the 60 foot elevations. It will be seen from this that the 8 p. m. temperature at the height of the shelter usually represents well that of a thick blanket of air which overlies the lower air strata over a bog and from which the air drainage will mostly take place during the night. This is why the 8 p. m. shelter temperature is of such value in the new method of predicting.

2. The selection of a multiplier, for each reading number and rise amount of the barometer correlation table (Table 4), that would produce a "forecasting factor 2" giving as accurate predictions as possible on windy nights (with an 8 p. m. velocity of 6 or more miles an hour) when averaged with "forecasting factor 1." These multipliers were obtained by a process of repeated trial and rejection.

3. The development of the air-drainage table (Table 5) for still nights (with an 8 p. m. wind velocity of 6 or less miles an hour), using the average of "forecasting factor 1" and "forecasting factor 2" as obtained for windy nights as a base from which to determine the effect on the bog minimum temperature of different amounts of air drainage as indicated by the 8 p. m. wind velocity.

4. The discovery of the various corrections.

Table 9 compares the results of calculating minima for the station bog on still nights by the writer's method with the results by the equation $Y = a + bR$. The equation seems to be valuable mainly because it can be used two or three hours earlier in the day than the new method, it seeming the less accurate.[14]

Both these methods use the early evening dew point and temperature (for with any given dew point the relative humidity depends on the temperature).

TABLE 9.—*Comparison of the results of computing bog minima on clear, still nights by the hygrometric equation and by the writer's method.*

Date.	Error with the equation $Y=a+bR$.	Error with the new method.	Date.	Error with the equation $Y=a+bR$.	Error with the new method.
1913.			1915.		
May 26	−3.2	−1.2	Oct. 10	+1.1	−1.0
Sept. 10	−2.0	−1.0	1916.		
14	+1.2	+1.2	Sept. 11	+0.3	+2.0
15	+1.0	+0.8	17	+0.6	(1)
1914.			Oct. 1	−4.0	(1)
June 2	+0.9	+1.5	2	−1.1	−1.2
Sept. 10	+0.8	−0.2	1917.		
11	+0.6	+0.5	Sept. 8	−1.1	+0.5
12	+6.1	+2.2	11	+0.9	+0.8
1915.			22	−3.9	+0.2
Sept. 22	+0.6	+1.5	Oct. 16	−1.4	−2.0
30	+2.0	+2.2			
Oct. 9	+1.1	+2.0	Average errors	1.7	1.2

[1] Records not full enough to reckon by this method.

These are the first reasonably reliable methods made available for computing bog minima. A fair idea of the coming minimum under anticyclonic conditions may be gained by them often by 6 p. m. on still nights and usually by 8 o'clock even on windy ones. As damaging frosts may occur as early as 11 p. m., this warning sometimes will give only 3 hours in which to flood. Frost-flooding can be done on many bogs in this time, but it takes several hours more on most of the larger areas with their present flumes and canals. Many growers would profit by greatly enlarging these equipments so as to flood more quickly and make full use of the warnings obtained by the new methods.

WIND VELOCITIES.

As has been long known, average wind velocities in all parts of the world go through a diurnal cycle in which the maximum is reached in mid afternoon and the minimum from 3 to 8 a. m. This cycle is supposed to be due to convection. It is shown well in the Report of the Chief of the Weather Bureau for 1896–97, pages 110 to 123, inclusive, this giving the average hourly velocities

[14] In actual forecasting in 1918, the equation often proved very unreliable as compared with the new method. (See the note following Table 1.)

monthly for the five years 1891–1895 for 28 stations in various parts of the United States.

Figure 1 illustrates the variations in the average hourly wind velocity at Boston, Mass. It shows that this velocity increases rapidly from the seventh hour in the morning until the first in the afternoon; that it then changes slowly until the fourth hour, from which until the eighth it decreases very rapidly, and that from the eighth hour in the afternoon until the eighth in the morning the change is much slower than during the rest of the day except the first three hours after noon.

The writer tried to develop the new system of computing from 6 p. m. observations but failed to find a reliable formula for that hour. The fact that the afternoon wind velocity usually changes rapidly until the eighth hour, as here shown, accounts partially for this,[15] a velocity at all representative for the night probably not being reached as a rule before that time.

Table 10 shows that velocities on frosty nights on the Cape usually change according to the general rule, but that their average decrease is greater.

TABLE 10.—*Average wind velocities on frosty nights in seasons of frost danger at the cranberry station, East Wareham, Mass., 1913 to 1918, inclusive.*

Year.	Nights averaged.	Average velocity (miles per hour).			
		At 6 p.m.	At 8 p.m.	At 10 p. m.	12 to 6 a. m.
1913	10	4.87	1.86	2.07	2.74
1914	14	4.81	2.87	....	2.45
1915	13	6.00	4.00	3.57	4.0
1916	13	3.00	3.00	2.18	2.5
1917	28	5.25	5.37	4.00	3.5
1918	40	4.76	3.81	3.82	3.15
Averages of the 118 nights	....	4.83	3.84	3.46	3.14

In developing the new method of predicting it was found that the 8 p. m. velocity often failed to measure fairly that for the night, because it did not follow the usual changes. The writer tried to learn when this velocity is abnormal and how to allow for its aberration in computing. His studies were based on the relative wind velocity at 6 p. m. and 8 p. m. The conditions of this relationship inspected and the findings about it follow:

1. *When the barometer rises strongly from 4 to 8 p. m. and the wind increases from 6 to 8 p. m., the velocity being not less than 3 miles at the former and not less than 6 miles at the latter hour.*—The ratio under these conditions found between the average of the 8 p. m. velocities and the average of the average 12 to 6 a. m. velocities is 2.46 and that between the average of the 8 p. m. velocities and the average of the minimum velocities is 4.06. When the conditions here considered occur, one usually can determine roughly the average 12 to 6 a. m. and minimum velocities by dividing the 8 p. m. velocity by these ratios. *It seems advisable to substitute the 12 to 6 a. m. velocity thus obtained for the 8 p. m. velocity in computing "forecasting factor 2" in the new method of reckoning minima, for the latter velocity with these conditions usually is not representative, but shows a temporary and probably local increase.* The writer's records show that an increase of the wind from 6 to 8 p. m., even if the barometer does not rise strongly between 4 and 8 p. m. and the velocity is less than 3 miles at 6 p. m. and less than 6 miles at 8 p. m., is very commonly temporary and misleading. It seems best, therefore, to discount any such increase by dividing the 8 p. m. velocity by the ratio 2.46 and substituting the quotient in computing.

2. *When the velocity is the same at 6 and 8 p. m. and is not less than 1.5 miles at those hours.*—Nothing of special

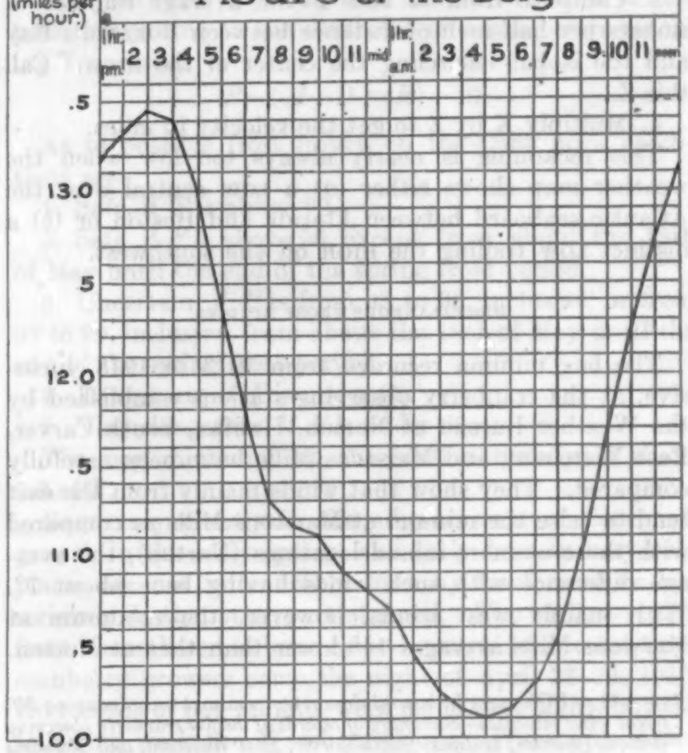

FIG.—Variations in average hourly wind velocity at Boston, Mass.

value in calculating temperatures was found in this relation.

3. *When the velocity decreases half or more from 6 to 8 p. m.*—It was found that while the wind usually does not increase under these conditions during nights in the spring, the minimum velocity coming after midnight in more than half the cases, it tends to do this more in the summer, and does it nearly always in the fall, the lowest velocity seldom coming after midnight in that season.

In applying the new way of reckoning minima to the records of the station, the writer has found it conducive to accuracy to correct the 8 p. m. computation at 10 p. m. by substituting the wind velocity of the latter hour when an

[15] "As is well known, the barometric oscillation attains, except in a few localities, two maxima and two minima every 24 hours, the minima occurring between 2 and 4 o'clock of the early morning and afternoon, and the maxima between 8 and 11 of the forenoon and evening." (Weather Bureau Bulletin 6, 1892, p. 7.) On this account, one often can not get a fair measure of the evening rise of the barometer much before 8 p. m. Moreover, the sun does not set until after 7 during most of the spring frost period.

increase occurs between the two hours. This increase seems to keep up usually during the rest of the night, or, when it does not, to unsettle conditions so as to raise bog minima almost in proportion to its amount. It seems to be due usually to an increase in distant cyclonic activity. As stated above, it always may be expected in the fall after a velocity decrease of half or more from 6 to 8 p. m.

The writer has found that if a wave of high pressure is approaching, the average wind velocity from midnight to 6 a. m. on cold nights usually may be calculated roughly as follows:

1. Count, on the morning weather map issued by the Boston office of the Weather Bureau, the isobars between Buzzard's Bay and the isobar surrounding the center of the approaching HIGH. Call the number X.
2. Measure in half inches the distance on the map between Buzzard's Bay and the isobar encircling the center of the HIGH. Call this number Y.
3. Compute from X and Y the average number of isobars per half inch of distance between Buzzard's Bay and the isobar encircling the center of the HIGH. Call this Z.
4. Multiply X by Z to get the velocity in miles.

This reckoning is nearly always too low when the weather map shows either (*a*) a LOW central over the Atlantic seaboard between Florida and Boston or (*b*) a distinct LOW trailing the HIGH on the southwest.

MISCELLANEOUS FROST STUDIES.

The bog minima recorded from 1913 to 1918, inclusive, at the cranberry observing stations established by the Weather Bureau at Norton, Halifax, South Carver, East Wareham, and Marstons Mills have been carefully compared. They show that winds mainly from the east tend to raise the minima at Marstons Mills as compared with those at more inland locations (Norton), the average difference with such winds having been about 7°. With mainly west winds, however, the minimum at Marstons Mills averages $1\frac{1}{2}$° lower than that at Norton.

TABLE 11.—*Differences in bog minimum temperatures accompanying different wind velocities—Summary of records of the five cranberry observing stations (Norton, Halifax, South Carver, East Wareham, and Marstons Mills) on cold nights in the frost danger periods of 1913 to 1918, inclusive.*

Average wind velocity at the station at East Wareham, Mass., from midnight to 6 a. m. (miles per hour).	Nights considered.	Least extreme difference between the observing stations.	Greatest extreme difference between the stations.	Average extreme difference between the stations.
		°F.	°F.	°F.
$1\frac{1}{2}$ or less	22	1	8	3.6
$1\frac{1}{2}$ to 3, inclusive	39	1	[1] 15	4.4
3 to 5, inclusive	29	1	[2] 15	5.1
More than 5	10	2	10	6.1

[1] One occurrence—probably an incorrect record at Marstons Mills, the greatest difference between the four other stations that night being only 5°. Next to this, the greatest difference recorded with this wind velocity was 9°, which occurred twice.

[2] One occurrence—possibly an incorrect record at Norton, the greatest difference between the four other stations being only 12°.

Table 11 exhibits the differences in the bog minima recorded at the observing stations named. These are often surprisingly large, averaging much greater than the errors made in computing the station minima.

The table also shows that the minima of the various stations average to differ considerably more on windy nights than on still ones. This seems surprising, as upland minima generally vary most on still nights, the air drainage being greatest with the least wind. As cranberry bogs are nearly level and are almost always at the very bottom of the basins containing them, they seldom fail to get the full effect of air drainage on still nights. This factor, therefore, may have little to do with differences in their minima. On Cape Cod, strong winds from the sea often raise minima of bogs near the coast several degrees as compared with those of areas a few miles inland. Moreover, the proximity of the ocean may cause greater variation in wind velocity on windy nights in different parts of the Cape section than occur in most inland regions of equal extent.

Probably the dew point and atmospheric pressure are usually fairly uniform over the whole Cape. It should be possible, therefore, to reckon the minimum temperature for any bog fairly accurately from East Wareham data if the temperature and, perhaps, the wind velocity at 8 p. m. in an elevated location near it are known.

The results of predicting for the Atwood[16] bog at South Carver on clear nights in 1918, exhibited in Table 12, indicate this is so. Mr. L. M. Rogers, the manager of the bog, kindly telephoned his 8 p. m. shelter temperature[17] to the writer and this was substituted for that of the station in computing the Atwood bog minima, the other data used in the reckoning being taken from the station instruments.

TABLE 12.—*8 p. m. shelter temperatures, computed bog minima and recorded bog minima of the Atwood bog, South Carver, Mass., and of the station bog, East Wareham, Mass., compared.*

Date.	8 p. m. shelter temperature.		Bog minimum computed.		Bog minimum recorded.		Computation error.	
	At station.	At Atwood bog.	For station.	For Atwood bog.	At station.	At Atwood bog.	Station.	Atwood bog.
1918.	°F.	°F.	°F.	°F.	°F.	°F.	°F.	°F.
May 11	51.0	46.0	33.7	31.2	35.0	32.0	−1.3	−0.8
May 15	52.0	45.0	30.5	27.0	29.7	29.0	+0.8	+2.0
May 16	50.5	49.0	29.2	28.5	27.0	28.0	+2.2	+0.5
June 8	58.0	52.0	35.7	37.0	34.0	36.0	+1.7	+1.0
June 20	47.0	43.0	26.7	24.7	26.7	25.0	0.0	−0.3
June 24	56.5	54.0	37.0	36.5	36.0	36.0	+1.0	−0.5
Aug. 27	54.0	51.0	33.7	32.2	33.0	31.0	+0.7	−1.2
Sept. 21	50.0	45.0	30.7	28.2	30.5	27.0	+0.2	+1.2
Sept. 22	49.0	43.0	30.0	27.0	27.0	26.5	+3.0	−0.5
Sept. 24	48.5	44.0	30.7	28.4	29.0	26.5	+1.7	+1.9
Sept. 27	52.0	47.0	29.7	27.2	34.0	32.0	−4.3	−4.8
Sept. 29	53.0	49.0	28.0	26.0	25.0	24.0	+3.0	+2.0
Oct. 1	41.0	38.0	23.0	21.5	25.5	21.0	−2.5	+0.5
Oct. 4	51.0	43.0	30.5	26.5	30.5	28.0	0.0	−1.5
Oct. 7	46.5	42.0	26.5	24.2	29.0	25.5	−2.5	−1.3
Oct. 8	37.5	32.0	21.0	18.2	19.7	18.0	+1.3	+0.2
Oct. 9	43.5	38.0	29.2	26.4	30.5	29.0	−1.3	−2.6
Average error, 17 days							1.6	1.3

[16] The Atwood bog is $8\frac{1}{4}$ miles (air line) from the station.

[17] The shelter thermometers at the Atwood bog are 18 feet 8 inches higher than the bog thermometer and about 335 feet from it. They are only 4 feet 2 inches from the ground.

Table 13 summarizes the records of the change of the dew point on frosty nights, classifying them according to the changes in atmospheric pressure.

TABLE 13.—*Changes of dew point accompanying different increases of atmospheric pressure on frosty nights—Records of station at East Wareham, Mass., 1913 to 1918, inclusive.*

Nights averaged.	Barometer rise from 4 p. m. to 6 a. m.	Nights dew point rose.	Nights dew point fell.	Nights dew point did not change.	Greatest rise of dew point in any night.	Greatest fall of dew point in any night.	Average change of dew point during night; + = rise, − = fall.
					°F.	°F.	°F.
16	−0.03 to 0.02, inclusive	13	3	0	11	15	+3.00
14	+0.02 to 0.06, inclusive	8	4	2	10	5	+2.36
23	0.06 to 0.10, inclusive	13	8	2	15	7	+2.33
19	0.10 to 0.15, inclusive	8	10	1	12	6	+0.13
38	0.15 and more	15	22	1	9	14	−2.11

It was thought the shifting of the dew point would so affect minimum temperatures as to make accurate predicting impossible, but it seems this change is offset largely by conditions accompanying it. For example, the fall of the dew point that takes place with the clearing of a storm and the rapid development of anticyclonic conditions is balanced for the night it occurs, as far as temperatures are concerned, by the high wind that comes with it.

A fall of the bog minimum more than 17° F. below the evening dew point occurred at the station twice in the spring and 16 times in the fall in the years 1913 to 1918, inclusive. All but one [18] of these occurrences were associated with long dry periods. All the minima more than 18° below the dew point except one [19] followed one or another of the dangerous map types described above. The greatest fall of the bog temperature below the dew point in the spring was 21°, and in the fall was $23\frac{1}{2}$°.[20] With the barometer below 30.3 at 8 p. m., the greatest fall below the dew point was 21°, and with it below 30.0, $19\frac{1}{2}$°.

For roughly predicting bog minima at 2 p. m., the writer finds the following formula useful:

F being the index, let:

M = the maximum shelter temperature for the day up to 2 p. m. (°F.).

D = the dew point at 2 p. m. (°F.).

B = the difference in tenths of an inch between the barometer reading at 2 p. m. and 29.9 inches if the local 2 p. m. pressure is less than 29.9 inches.

T = the difference between the average temperature on Cape Cod and the average temperature either over northern Lake Superior or near the center of the approaching HIGH (whichever had the lower temperature) shown by the isotherms of the morning weather map (°F.).

P = the number of tenths of an inch difference in pressure between the center of the approaching HIGH and the center of the northeast (New Brunswick or thereabout) LOW shown by the morning weather map.

Formulæ:—1. With anticyclonic conditions not accompanied by any of the dangerous types of pressure distribution described in this paper,

$$F = M + D + 4B.$$

2. With dangerous map types 1, 4 (whether the center of the approaching HIGH is west of the Port Arthur, Ontario, to Port Arthur, Tex., line or not), and 5,

$$F = (M + D + 4B) - \frac{4T}{P}.$$

3. With dangerous map types 2, 3, and 6,

$$F = (M + D + 4B) - 20.$$

4. When the map is dangerous type 3, but with the isobars between the HIGH and the western area of low pressure turning to the southeast or south before reaching Tennessee,

$$F = (M + D + 4B) - 10.$$

As to possible frost injury on the Cape bogs, conditions are:

1. Safe, if F is above 99.
2. Safe, if F is above 96, except from about the 18th of May until the end of the spring frost period.
3. Uncertain, if F is from 93 to 96, inclusive, or from 93 to 99, inclusive, from about the 18th of May until the end of the spring frost period.
4. Dangerous, if F is under 93.
5. Very dangerous, if F is under 90.

The bog minimum at the station usually is about 0.3 of F.

Bogs vary greatly in the advancement of their new growth in the early spring, and early bogs in very cold places are not infrequently hurt by frost more or less seriously in the latter part of April. The earliest spring frost remembered to have caused general loss to the Cape cranberry growers came the night of April 28–29, 1910. No records of bog minima were made that night, but the following week the Wareham Courier, Wareham, Mass., stated that they ranged from 17° F. to 23° F. Both March and April had been very abnormally warm and the season was fully two weeks ahead of the average when the frost came. The writer found by counting that from 10 to 75 per cent of the buds were killed on the various exposed bogs according to their condition and circumstances. Much harm was done even where the winter water had been let off only a day or two.

The latest spring frost recorded as harming the bogs came the night of June 20–21, 1918, when the bog temperature fell to $26\frac{1}{2}$° F. at the station and to 23° F. on some bogs. This frost reduced the crop prospect, as estimated, over half, and so hurt the vines on many bogs as to much reduce their possible 1919 crop as well.

Bogs in the coldest localities sometimes have suffered much loss by frost in the latter part of August, but the

[18] Sept. 24, 1918.
[19] Sept. 12, 1917.
[20] One instance, the next greatest being 22°, which occurred three times.

earliest fall frosts remembered as causing widespread cranberry loss on the Cape came the nights of September 10–11 and 11–12, 1917.[21] The spring and early summer having been late, cold, and wet, the cranberry crop was very tardy in ripening, the berries being still in a green or slightly colored condition on the nights mentioned. The bog minimum recorded at the station on the first night was 24½° F., and on the second 26° F. The first night the wind at the station was from the northeast with a velocity of 10 miles an hour at 8 p. m. and an average of 3⅞ miles from midnight to 6 a. m. This wind was generally, though, as it proved, unwisely relied on by the growers to prevent a hard frost. Temperatures as low as 18° F. were reported from some bogs, severe injury being common except in Barnstable County and on the Vineyard and Nantucket, all of which excaped with little or no hurt. The second night, however, bogs in Barnstable County suffered much loss. Mr. V. A. Sanders, field agent of the Bureau of Crop Estimates, set the total cranberry loss for both nights as follows: Plymouth County, 67 per cent; Barnstable County, 37 per cent.

On still, cold nights in the frost seasons the smoke of torches shows that the air movement at a man's height is always toward the bog from every side, whatever the general wind direction is. This shows that the bogs at such times radiate more heat than the low upland near them and probably explains why their margins are hurt by frosts oftener than their other parts.

CRANBERRY FROST ENDURANCE.

It has been found that in the spring cranberry winter buds will endure a temperature of 25° F., and possibly one even somewhat lower than this, without injury until they swell to a cross diameter of more than 2 mm.

The writer has never known a temperature above 29° F. to harm a cranberry bog. Often 28° is reached in the period of very tender growth without injury, but in such cases the greatest depression lasts only a short time.[22]

In the greenish-white stage that precedes ripening cranberries will stand 26° F. without hurt and 25° F. with little injury, but 24° F. seems to harm such fruit greatly if it lasts long.

Freezing begins among ripe Early Black and Howes berries at or slightly above 22° F., no softening following exposure to 23°. Ripe Howes berries are so resistant that under bog conditions often only 10 per cent freeze at a temperature of 16° F. and only 20 per cent at 14° F. Sometimes, however, 25 per cent are softened by 18° F. With Early Black berries the loss at these temperatures is always much greater. The Bugle, Chipman, and Atkins varieties are said to be especially frost tender. The records of the cranberry station from 1911 to 1918, inclusive, show that no bog temperature to harm well-colored berries much occurred there in any picking season of those eight years, it never falling below 22° F. before October 1 or below 20° F. before October 10. It seems from this that on Cape Cod, for bogs in warm or average locations that are flooded by pumping it hardly pays in the long run to try to protect well-colored berries from frost unless the crop is heavy.

As a result of his study of potential minima, the writer thinks the station bog crop is immune from frost injury until September 18, except when it ripens very late.

The writer has observed, as did Prof. Cox,[23] that a large majority of the cranberries that freeze in a frost in the picking season often thaw out without showing injury. If the temperatures are not too severe, they probably will usually endure repeated freezing and thawing without great deterioration. Such treatment, however, is certainly not beneficial.

Frost in cranberries can be detected most readily with one's teeth, the "bite" being very characteristic. The frozen berries also rattle strikingly when shaken together.

WAYS TO PROTECT BOGS FROM FROST.

Orchard heaters have been found impracticable for protecting cranberry bogs because of the expense involved, the fire risk and the injury done the vines by the necessary tramping, and the slopping of the oil.

Tobacco shade cloth also has been tried, with results as follows:

(*a*) This protection is not satisfactory on bogs with much moss under the vines because of their reduced radiation.

(*b*) Good second-hand cloth is so hard to get that its use is not feasible.

(*c*) One thickness of new cloth is not enough.

(*d*) The difficulties and expense of wire supports prohibit their use.

(*e*) Two thicknesses spread on the vines probably are enough protection for most Cape bogs, and this seems the best way to use it. It is too bulky to handle easily on large areas, but it may be left spread on a bog continuously for several days without reducing the protection.

(*f*) It is better to protect with water if it can be done with tolerable expense.

To protect a cranberry bog from frost by flooding, the water must be raised to a depth of an inch at all places under the vines. Because of the high specific heat of water, this amount usually will radiate warmth enough to maintain a safe temperature. Some growers claim the vines must be submerged under extreme conditions, but the writer never has known this to be necessary. Mere filling of the ditches is no protection beyond a few feet from the water. A heavy mist is no proof against frost injury and the smoke from fires near the bog margin is no help, their heat alone giving protection and that for only a short distance.

A clean sand mulch under the vines protects against frost to quite an extent.[24] It is probably most effective when the sand is wet.[25]

[21] These frosts did not seem to harm the terminal buds, and thus affect the 1918 crop, anywhere (Cox, op. cit., p. 121).

[22] Cox, op. cit., p. 118.

[23] Op. cit., p. 91.

[24] Bul. No. 150, Mass. Agr. Expt. Sta., 1914, p. 39.

[25] Bul. No. 160, Mass. Agr. Expt. Sta., 1915, pp. 91–93.

FORECASTING MINIMUM TEMPERATURES.

GEO. S. BLISS, Meteorologist.

[Dated: Philadelphia, Pa., Dec. 10, 1918.]

The writer's experience in the forecasting of minimum temperatures has been confined chiefly to the winter season, the forecasts being made for the benefit of shippers and handlers of perishable goods. Experience in frost forecasting has consisted of a very brief study of the conditions on the cranberry marshes of New Jersey.

During the winter season the chief factor to consider in the work is the movement of air masses, while in frost forecasting for the cranberry bogs the chief factor is radiation conditions.

In winter forecasting use must be made of pressure and temperature change maps, but in order to interpret them correctly one must also consider the abnormal temperature departures in the regions from which the air masses are approaching. The statements regarding the movement of air masses are not intended to mean that there is a complete translation of air masses at the same rate as the storm movement, but the effect on temperature changes is much the same as if that were true.

For example, let us suppose a rapid rise in pressure in the upper Lake region, with a 24-hour fall in temperature of from 20° to 25°, and with fresh northwest winds over a wide area. If this temperature drop was from normal conditions and if the temperatures at the same time are near the normal in Pennsylvania then the temperatures in Pennsylvania may be expected to fall to 20° or 25° below the normal. On the other hand, if the 20° to 25° drop in the upper Lake region served only to restore normal conditions, and the temperatures at the time are near the normal in Pennsylvania, then no marked change should be expected in Pennsylvania with the eastward translation of the disturbance.

Damaging frosts on the cranberry marshes more often occur on the night after the chief rise in pressure when the winds have quieted and when cool, dry air overspreads the region. A moderate or even gentle wind movement tends to prevent frost, while absolute calm is highly favorable for its formation.

Since the conditions for frost on the marshes are nearly all local in character, it is believed that a radiation formula can be calculated for each locality and used to good advantage. This, however, would be impracticable in winter forecasting since, as has been stated, the change in temperature is mainly dependent upon a change in the local conditions.

When the marshes are immediately adjacent to or are surrounded by wooded areas there is created a local condition that will always be difficult to cope with, no matter what may be the method of procedure. Under such conditions the cooling by radiation proceeds rapidly during a calm, but the temperature rises quickly upon a slight movement of the comparatively warm air from under the trees out over the marshes. The effect on the temperature trace is sometimes to make it resemble a record from a Dines wind pressure instrument during a gusty wind. Evidently the actual minimum temperature will be dependent upon the wind conditions at the hour when a minimum temperature should be reached.

PREDICTING MINIMUM TEMPERATURES IN THE NEW ORLEANS, LA., DISTRICT.

By I. M. CLINE, District Forecaster.

[Dated: Weather Bureau, New Orleans, La., May 9, 1919.]

Forecasts of expected minimum temperatures are based on studies of high-pressure areas and attendant minimum temperatures as they appear in the Northwest and the resultant pressure and temperature conditions which have occurred in the west Gulf district in the following 24 to 36 hours. It has been found that by interpolating for differences in intensity of pressure and the degree of temperature in somewhat similar types, minimum temperatures for limited areas can be successfully forecast 24 to 36, and in some instances 48 hours in advance of their occurrence, thus giving time for the extensive protection of agricultural crops, live stock, and other interests.

The expense of protection is considerable; therefore, forecasts of minimum temperatures to be of value must not only be accurate but, as a rule, where considerable areas are to be protected, they must be far enough in advance to enable those who use the warnings to make extensive preparations to guard against injury. We have met these conditions in forecasting the minimum temperatures in every important freeze which has occurred in the New Orleans district.

From October 1 to April 30, interest centers in the lowest temperature, and we now include regularly in the a. m. forecast a statement of the lowest temperature we expect the following morning.

PREDICTING MINIMUM TEMPERATURES.

By W. S. Belden, Meteorologist.

[Dated: St. Joseph, Mo., July 18, 1919.]

In order to meet the need for close predictions of minimum temperatures in orchards in the vicinity of St Joseph, Mo., during the critical periods of frost and freezing temperature in spring and fall, a study of this subject has been carried on since the spring of 1918. The study is based on special temperature and hygrometric observations made in the Kenmoor apple orchard, near De Kalb, Mo.; in the Woodson orchard, near Agency, Mo.; and the records of the weather observatory in St. Joseph.

The methods of procedure in this work are similar to those used by Prof. J. Warren Smith in Ohio.[1] The object of the investigation is to supplement the general forecasts of the Bureau with a close prediction of the minimum temperatures that will probably be experienced in individual orchards on nights favorable for free radiation, thus furnishing the orchardist information concerning impending danger to fruit buds, blossoms, or mature fruit in time to permit the effective employment of protective methods, such as smudging, etc. It is proposed to maintain the substations for a few years for the purpose of developing and establishing the thermal relationship of the temporary stations to the permanent station at St. Joseph, after which they may be discontinued.

The Agency station is located in the comparatively level Platte River Valley and has an elevation above sea level of approximately 830 feet, while the De Kalb station is situated on high, rough land about 1 mile from the Missouri River bottom and has an elevation of approximately 1,075 feet. The topography of the two stations, especially with respect to elevation, is near the extremes for this section, although the De Kalb station is regarded as being fairly representative of the topographical conditions of the greater portion of the numerous apple orchards within a radius of 20 miles of St. Joseph. The St. Joseph station has an elevation of 967 feet and is located on a hill about 2,250 feet from the Missouri River and approximately 170 feet above it.

Thus far local investigations have been directed primarily along two lines of study, known as the median-hour and hygrometric methods of predicting minimum temperatures.

(1) *Predicting the minimum temperature from the median temperature hour.*—The halfway temperature between the maximum one afternoon and the minimum the following morning, when the night is clear and favorable for radiation, is known as the median temperature, and if the hour of its occurrence at a given place is found to have small variation for any given month a basis is established for predicting the minimum temperatures for that place. Table 1 gives the average median temperature hours for each of the three stations under discussion, the record for St. Joseph covering a period of nine years, but the values for the two fruit-frost stations are for two seasons only.

Table 1.—*Average median temperature hours.*

[90th meridian, normal time.]

Station.	Apr. 1 to May 15.	Sept. 15 to Oct. 31.
	P. M.	*P. M.*
Agency	8:01	6:51
De Kalb	8:11	7:24
St. Joseph	9:33	8:39

The values in Table 1 show that the median hour is reached about one hour and a half later in the city than at the orchard stations. In extreme cases the variation in the time of occurrence of the median temperature at each station from the median temperature hour is slightly more than two hours, but at St. Joseph the variation amounts to less than one hour in 81 per cent of the cases, and at Agency in the spring, with two seasons considered, the variation is less than 32 minutes in 80 per cent of the cases. The variation at De Kalb is somewhat greater than at St. Joseph. When the median-hour method is employed in connection with the hygrometric method, as indicated in Table 3, it appears to be an aid in securing good results.

(2) *Predicting the minimum temperature from the hygrometric method.*—Least squares.[2] In Table 2 the method of least squares is used to determine the relation between the relative humidity and dew point of the evening and the minimum temperature the following morning.

Table 2.—*Evening relative humidity, R, and the variation of the minimum temperature of the following morning from the evening dew point, Y, at St. Joseph, Mo., for those dates in the spring of 1918, when conditions favored radiation.*

Date.	R	Y	R^2	RY
Mar. 24	20	+18	400	+360
25	23	+24	529	+552
26	29	+ 1	841	+ 29
31	32	+ 9	1,024	+288
Apr. 1	21	+16	441	+336
6	34	+13	1,156	+442
8	19	+18	361	+342
9	18	+19	324	+342
10	15	+19	225	+285
11	27	+12	720	+324
12	38	+ 5	1,444	+190
17	29	+16	841	+464
30	22	+20	484	+440
May 1	32	+18	1,024	+576
2	27	+16	729	+432
3	30	+17	900	+510
10	32	+14	1,024	+448
13	30	+14	900	+420

$n=18 \quad \Sigma R=478 \quad \Sigma Y=269 \quad \Sigma R^2=13,376 \quad \Sigma RY=6,780$

$$Y=a+bR.$$

$$b=\frac{n(\Sigma RY)-(\Sigma R)\ (\Sigma Y)}{n(\Sigma R^2)-(\Sigma R)^2}=-.533$$

$$a=\frac{\Sigma Y-b\ (\Sigma R)}{n}=29.1$$

$$Y=a+bR=29.1-.533R.$$

[1] Monthly Weather Review, August, 1917, 45: 402-407.

[2] Prof. C. F. Marvin, Monthly Weather Review, October, 1916, 44: 551-569.

R is the relative humidity in the evening and Y the departure of the minimum temperature the following morning from the evening dew point. By substituting the values of R given in Table 2, the values of Y have

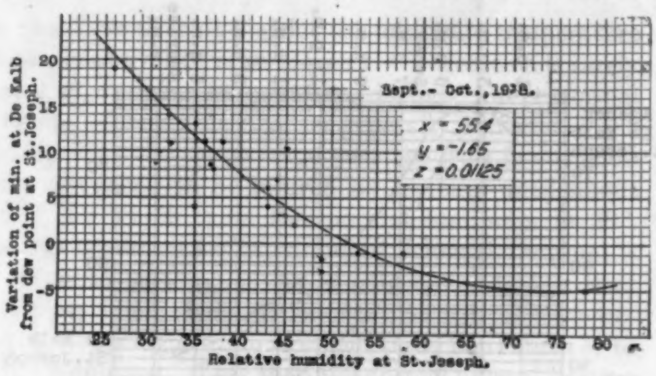

FIG. 1.—September and October, 1918. Hygrometric data at St. Joseph, Mo., minimum temperature at De Kalb, Mo.

been calculated and appear in Table 3. In Table 3 also appears minimum temperature values determined by the median hour method and the minimum temperatures as estimated from a mean of the two methods. By ref-

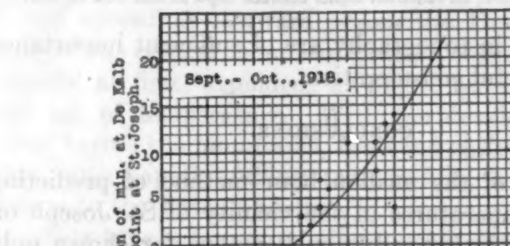

FIG. 2.—September and October, 1918. Hygrometric data at St. Joseph, Mo., minimum temperature at De Kalb, Mo.

erence to the last column in Table 3, it will be noted that the variation of the estimated minimum temperatures from the recorded minimum readings was 3° or less in 15 out of 18 instances.

TABLE 3.—*Minimum temperature estimates for St. Joseph, Mo., when conditions favored radiation, using hygrometric and median temperature methods, and a combination of both with corresponding errors.*

Date.	Minimum temperature recorded.	Computed by equation $Y=a+bR$.	Error by this method.	Computed by median temperature method.	Error by this method.	Estimated from mean of first two methods.	Error by this method.
1918.							
Mar. 25	40	40	0	40	0	40	0
26	53	46	− 7	50	− 3	48	−5
27	36	49	+13	21	−15	35	−1
Apr. 1	41	44	+ 3	40	− 1	42	+1
2	47	49	+ 2	55	+ 8	52	+5
7	40	38	− 2	40	0	39	−1
9	31	32	+ 1	31	0	32	+1
10	30	31	+ 1	33	+ 3	32	+2
11	30	32	+ 2	34	+ 4	33	+3
12	37	40	+ 3	41	+ 4	40	+3
13	38	42	+ 4	37	− 1	40	+2
18	43	41	− 2	43	0	42	−1
May 1	40	37	− 3	43	+ 3	40	0
2	52	46	− 6	52	0	49	−3
3	54	53	− 1	52	− 2	52	−2
4	60	56	− 4	56	− 4	56	−4
11	46	44	− 2	47	+ 1	46	0
14	49	48	− 1	49	0	48	−1

(3) *Predicting the minimum temperature from the hygrometric method—Parabolic curve.*—In accordance with suggestions made by Prof. J. Warren Smith, the values given in Table 4, which are self-explanatory, have been

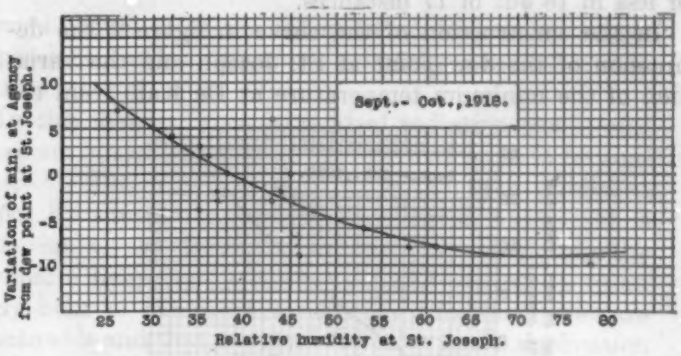

FIG. 3.—September and October, 1918. Hygrometric data at St. Joseph, Mo., minimum temperature at Agency, Mo.

employed in the preparation of figures 1–6. The method of solution and construction of the curve in figure 1 is explained by Prof. Smith in the first paper of this series. (See p. 6.)

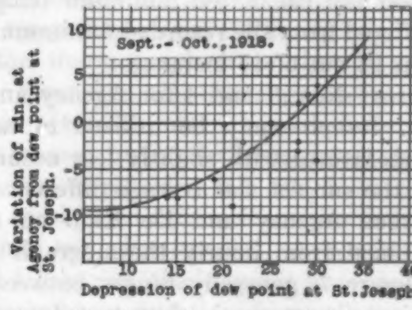

FIG. 4.—September and October, 1918. Hygrometric data at St. Joseph, Mo., minimum temperature at Agency.

As an example of the practical use that may be made of this curve, assume the following as values determined at St. Joseph at an evening observation in the latter part of September or October: Relative humidity 36 and dew point 37. Locate the point on the curve having a

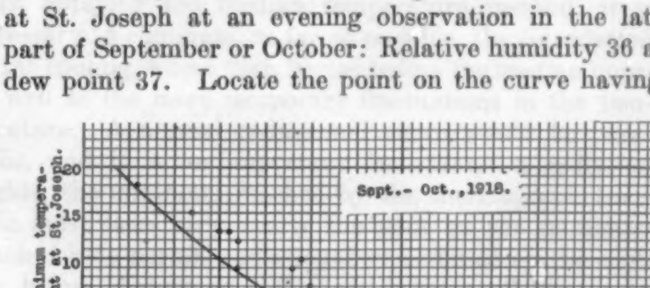

FIG. 5.—St. Joseph, Mo., September and October, 1918.

relative humidity value of 36 and note that this point has a corresponding value of 11 for the variation of the minimum temperature at De Kalb from the dew point at St. Joseph. The value 11 added to the dew point 37 gives 48°, which is the expected minimum tempera-

ture at De Kalb on the following morning. By this method the calculated minimum temperatures at De Kalb on radiation nights in the fall of 1918 differed from the actual or recorded minimum temperatures by 2° F. or less in 16 out of 17 instances.

In the construction of the curve in figure 2 the depression of the dew point at St. Joseph and the variation of the minimum temperature at De Kalb from the

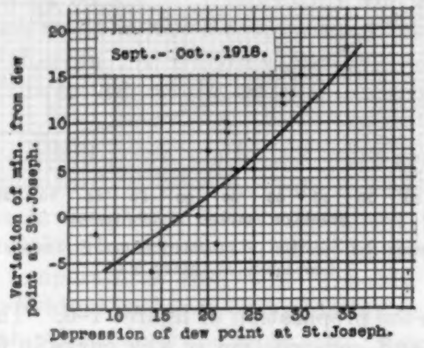

FIG. 6.—St. Joseph, Mo., September and October, 1918.

dew point at St. Joseph are used as the coordinates. By this method the calculated minimum temperatures at De Kalb differed from the recorded minimum readings 2° F. or less in 14 out of 17 instances.

Similar figures—Nos. 3 and 4 for Agency and Nos. 5 and 6 for St. Joseph—may be utilized in estimating minimum temperatures with slightly less accuracy.

Apropos to the subject the average difference in temperature between Agency and De Kalb on radiation nights, determined from hourly thermograph readings, as shown in figure 7, generally ranges between 6° and 9°. The fall in temperature is abrupt at Agency within the hour following sunset, but the greatest temperature differences between the lowland and highland stations take place in the early morning. In connection with the setting out of new orchards in this section, it is believed that these variations in thermal conditions due

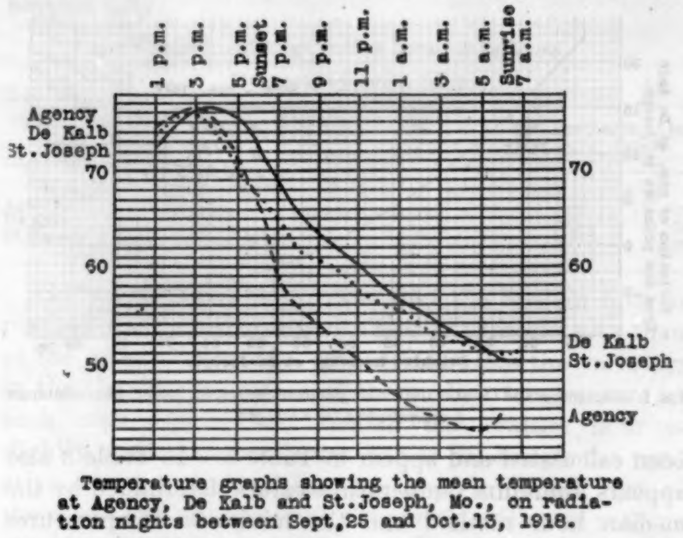

FIG. 7.—Temperature graphs showing the mean temperature at Agency, De Kalb and St. Joseph, Mo., on radiation nights between Sept. 25 and Oct. 13, 1918.

to differences in topography are of sufficient importance to justify careful consideration.

CONCLUSIONS.

The study of the median hour method of predicting minimum temperatures in the vicinity of St. Joseph on nights favorable for radiation has thus far shown only fair results, but the investigations indicate that hygrometric data at St. Joseph can be used in predicting the minimum temperature at substations with good results.

MINIMUM TEMPERATURE FORECASTING AT ROSWELL, N. MEX.

By Cleve Hallenbeck, Observer.

[Dated: Weather Bureau, Roswell, N. Mex., Dec. 27, 1918.]

In the Roswell fruit district the minimum temperature is normally above 30° after March 1. Vegetation is rarely injured by a higher temperature; in fact, under normal conditions of humidity, 28° is generally considered the critical point. In the average year the fruit is not sufficiently advanced to be injured by freezing until about April 1, at which time the normal minimum is 38°. Since the occurrence of a minimum below the normal is due either to an importation of cold air or to less than normal daytime heating, it follows that critical temperatures in the spring are due to one of these two causes or to the two combined. Less than the normal diurnal heating sufficient to result in any material reduction in the temperature is, in this district, always due to daytime cloudiness.

So far as this region is concerned, importations of cold air fall under two general types. One is the case of a HIGH moving south or southeastward west of the mountains and spreading eastward across the Divide in the latitude of the central mountain States. Here the wind is westerly at first, attended, at night, by a less than normal fall of temperature. With the development of the HIGH across the mountains, the wind shifts to northeasterly with rapidly falling temperature, a condition analogous to the Texas "norther."

The other type is a HIGH moving southeastward east of the mountains. In the majority of cases any decided inflow of cold air from this HIGH is attended by general cloudiness over the Roswell district, which, if prevailing at night, prevents critical temperatures being reached except in the infrequent cases where the inflowing air itself has a temperature at or below freezing.

With the first of these two types it is important for the forecaster to know, if possible, the approximate time when the shift of wind will occur. If at night, and especially if before midnight, critical temperatures will very likely be reached by morning; if in the daytime, the normal diurnal heating will be greatly decreased or entirely counteracted, so that further radiational cooling the following night will result in low temperature. It is a characteristic of this district that, in the absence of any inflow of warm air, a normal radiational fall of temperature will occur at night, regardless of how low the temperature may be at the beginning of the night.

In the case of the second type, it is important to know the approximate time when clearing will occur; if in the daytime or before midnight, critical temperatures are almost sure to result by the following morning.

In each case, the inflow of cold air is likely to last for 24 hours or longer, so that the second night is colder than the first, even when there is no importation of cold air during the second night. In fact, the coldest night nearly always occurs after the inflow of cold air is no longer appreciable, and is, therefore, primarily a radiation condition.

In this district, even with ideal radiation conditions, there are a number of other factors that have to be considered. These are discussed in detail in a published paper by the writer (M. W. R., August, 1918). It is sufficient to say here that methods of calculating the minimum temperature based upon the cooling up to an early hour of the night are the only methods that are practicable and that the chief difficulty in the application of such methods lies in the temporary departure of the temperature from the path of a true radiational curve. Hygrometric formulae can not be satisfactorily used, as the temperature in spring is normally 18° to 20° above the dew point and differences of 40° to 50° are not uncommon.

The problem before the local forecaster is calculating the normal temperature curve for any night from the portion of the thermograph trace that is available at 8 p. m. The most common thermograph trace on radiation nights is a smooth normal curve from about two hours before sunset until two hours after, followed by two to six hours of retarded fall, which, in turn, is followed by an accelerated fall until sunrise and sometimes until an hour or two after sunrise. As a rule, the earlier this retarded fall begins, the longer it lasts, and, where of but two or three hours duration, is usually a rise instead of a retarded fall. In addition, there are temporary irregularities in the temperature which may occur at any time of the night.

In applying the median temperature method, it is necessary to eliminate, as far as possible, the retardation in the cooling, where such begins before the median hour, as well as the more temporary fluctuations in the temperature. A normal radiational curve would be parabolic, and it is an important fact that, on radiation nights, the minimum reached by the thermograph trace is in most cases very nearly the same as the minimum reached by a normal radiational curve based on the cooling before disturbing influences became effective. In other words, the retarded cooling very nearly is counterbalanced by the later accelerated cooling, while other fluctuations in the temperature do not materially affect the minimum. It is the writer's practice, on occasions when the temperature evidently is not following a normal path, to project the unaffected earlier portion of the thermograph trace downward to the median hour, and to use the temperature indicated at that point by the projected curve, instead of using the actual temperature shown by the thermometer or thermograph trace. This results in greater accuracy than is obtainable through using the

uncorrected median hour temperature on nearly all—possibly all—nights when the cooling is not modified by an inflow of warmer of colder air.

It should be mentioned that in using the "corrected" median temperature it is necessary to use a mean median temperature hour that has been calculated from "corrected" thermograph traces.

Greater accuracy is often obtainable when the minimum temperature is not calculated until half an hour or hour after the median hour, as the additional record may enable one to calculate the probable normal curve for the night with greater accuracy.

The writer also has used with some success a method based upon the cooling from two hours before sunset until two hours after, the trace being corrected for temporary variations where such occur. Where this method indicates a range for the night much greater or less than normal, the actual range will in most cases be 1° to 3° nearer the normal than that indicated by the calculation.

While it has not yet been tried out in actual practice, the writer believes that there are times when a correction may be applied to the maximum temperature in applying the median temperature method. It frequently happens that the thermograph trace, for a period of from one to three hours during the warmest part of the day, shows a number of sharp rises and falls over a range of from 1° to 6°. This is without question due to the passage of alternate "waves" or masses of relatively cool and warm air. The temperature recorded by the maximum thermometer is the warmest part of the warmest "wave" and is not the mean maximum temperature of any considerable portion of the lower air. But, since this lower air is in constant motion and process of admixture, even on ideal radiation nights, it seems that the mean maximum temperature of the air would, if used, give more accurate results. In testing this out on past thermograph records, the writer finds that in about 7 times out of 10 it gives slightly better results than where the actual recorded maximum is used. The correction of the maximum is quite a simple procedure, as a few seconds inspection of the thermograph trace enables one to approximate a mean within a fraction of a degree.

Quite as important as the minimum temperature is the hour at which the temperature will reach a critical degree, and nearly as important as this, from the orchardist's viewpoint, is the rate of cooling after a critical degree is reached. This can be forecast with greater accuracy when there is a decided inflow of cold air than when the night cooling is entirely radiational, but even in the latter case it can often be done with satisfactory accuracy.

FROST AND MINIMUM TEMPERATURE STUDIES IN THE RIO GRANDE VALLEY PROJECT, U. S. R. S.

By ROBERT M. SHAVER, Observer.

[Dated: Weather Bureau, El Paso, Tex., Dec. 24, 1918.]

The climate of this portion of the Rio Grande Valley is such that its great staple fruit crop, pears, can be grown with the assurance that a fair crop will result without frost protection of any kind; consequently very few growers have thought it advisable to go to the expense of installing heating systems.

The valley is protected by high mountain ranges on the northwest, north, and northeast, and the cold northerly and northeasterly winds that bring low temperatures to northern and eastern New Mexico are tempered adiabatically before reaching here.

The upward march of temperature in the spring is rapid, and, within a short time after the beginning of the critical period for fruit, the average daily minimum temperatures are considerably above the danger point. A return to the danger point, should it occur, is usually indicated in advance by the weather map.

If the fall in temperature is occasioned by the passage of a LOW over this region and the advancement of a HIGH southeastwardly from the eastern slope of the northern Rocky Mountains, strong winds will rush down the valley in the wake of the LOW. The velocity of the wind will, as a rule, be least near the time of sunrise, or the coldest part of the day, but it will still be too strong at times to make orchard heating practicable.

On the following night, however, with high pressure obtaining, the air will be quieter, and the state of weather probably suitable to free radiation. The temperature will probably go as low, or a few degrees lower, than it did the night before, and the condition most favorable to frost, or injurious temperatures, presents itself.

Of the two general methods of estimating the minimum temperature of the following morning, on a night suitable to free radiation, by means of local observations, namely, the relative humidity and dew point and the median temperature methods, only the latter seems to be applicable in this dry region.

At El Paso, on clear nights, during the months of March and April, 1914 to 1917, inclusive, the average difference between the actual minimum temperatures and those arrived at by median temperature calculations was 2.5° for each month. The greatest differences were due to sudden rises or falls of several degrees after the time of the average median, caused by sudden changes in the wind direction.

PREDICTING OF MINIMUM TEMPERATURES IN COLORADO.

By F. H. Brandenburg.

[Dated: Weather Bureau, Denver, Colo., Nov. 21, 1917.]

It is noted that practical application of these (hygrometric) formulæ hinges on the existence of radiation conditions. Unfortunately the greatest damage in the valleys of western Colorado occurs almost invariably along the front of an advancing high-pressure area, following in the wake of a deep low-pressure area, rather than after radiation conditions set in.

NOTES ON DAMAGE TO FRUIT BY LOW TEMPERATURES; PREDICTION OF MINIMUM TEMPERATURES.

By Esek S. Nichols, Meteorologist.

[Dated: Weather Bureau, Grand Junction, Colo., Jan. 25, 1919.]

A special temperature-forecasting system is maintained by the Weather Bureau at Grand Junction, in the lower Grand Valley, Colorado, principally for the purpose of warning growers of deciduous fruits of the approach of damaging temperatures during the spring frost season, at which time of year the fruit trees of the Grand Valley (mainly peaches, apples, and pears) blossom and set fruit. Orchard heating is the principal method of protecting the orchards against the freezes.

DAMAGE TO FRUIT BY LOW TEMPERATURES.

A problem that has presented itself during practically every one of the eight seasons the writer has been in charge of the forecast work referred to has been the determining of the damage to the fruit resulting from particular freezes. We can, with comparatively little difficulty, find how much the temperature is raised by orchard heating on a given occasion and what the cost of heating has been; but it is usually difficult, if not impossible, to say exactly how much injury to the fruit has been prevented, how much the fruit crop has been bettered, and, especially, how much the operation has paid in dollars and cents. Primarily the investigation of the damage is the province of horticulturists; but meteorologists can be of much assistance.

Tables prepared by different horticulturists and purporting to show at what temperatures fruit buds, blossoms, and newly set fruit are killed do not agree. But these discrepancies are no longer surprising, since experience has shown that the critical temperatures vary from time to time, as is recognized by Chandler, who states, "Unquestionably there is a considerable difference in the killing temperature of bloom in different years." [1] Also, even on an individual tree, the fruit is not all equally affected by low temperature; when freezing occurs we expect to find fruit in one or more stages of development partly killed, partly injured, and partly uninjured. West and Edlefsen have well said, "A reading of the popular literature on the subject is likely to cause one to infer that buds have a certain definite freezing (killing) temperature, and that when they arrive at this temperature they all freeze (die). This, of course, is wide of the truth. * * * A freeze or two in early spring will usually do no harm; they simply serve to thin the buds out, for it is generally known that there are many times more buds on the tree than actually mature into fruit. The number that we can allow to freeze out and yet not heat the orchard will naturally depend on how many there happen to be on the trees at this particular time." [2]

On this account it sometimes happens that, although a heated orchard sets more fruit than a neighboring one that was not heated, the latter tract produces as good a crop as the former, the owner of which has, not only his heating expense without remuneration, but also additional outlay for thinning his crop by hand later in the season. It may, therefore, be wise for an orchardist, even though he be equipped to heat, to permit a portion of his bloom to be destroyed by freezing, especially if the bloom be heavy and the freeze occur late in the season. As a guide in this connection, the authors last mentioned have frozen branches, and even whole trees, by inclosing them in a freezing chamber, in an attempt to determine what temperatures kill certain percentages of the fruit at different stages of its development.

It is undoubtedly true that things in addition to the air temperature determine the amount of injury. These factors are numerous, and some of them are obscure. Many of them have been investigated. Chandler mentions, especially, concentration of cell sap, rapidity of temperature fall, previous exposure to low temperature, turgidity, maturity, variety, etc. Experience in the Grand Valley has shown that cloudiness and atmospheric moisture are important. While no extensive investigation of the matter has been undertaken, it has been noted that, when the air is very dry and clear, a given air temperature is commonly accompanied by an unusual amount of damage, while the same temperature, if accompanied by cloudiness and unusually high relative humidity, especially if the trees be dripping wet from recent precipitation, is followed by exceptionally light damage. An instance of the former condition occurred in the Grand Valley on the night of April 23–24, 1913.[3] The latter condition prevailed on the night of April 19–20, 1916, when, to quote from my report for that frost sea-

[1] The Killing of Plant Tissue by Low Temperature: Research Bulletin No. 8, University of Missouri Agricultural Experiment Station, p. 144.

[2] The Freezing of Fruit Buds, by F. L. West and N. E. Edlefsen. Utah Agr. Coll. Exper. Station Bull. No. 151, pp. 19 and 20.

[3] See my notes on "Damage by Frost in Western Colorado," Monthly Weather Review, April, 1913, 41: p. 608.

son, "* * * generally some snow remained unmelted or in a slushy condition adherent to the trees. At nightfall trees in the vicinity of Grand Junction were dripping wet. * * * In the early morning of the 20th I visited orchard districts near Grand Junction. Fruit was frozen solid and would break from the branches when the latter were struck sharply, particularly in the case of pears. * * * But the damage was surprisingly small over the valley as a whole, and sufficient fruit was left to produce a fairly good crop." Some of the blossoms may have been protected somewhat by an insulating layer of ice or snow, but the effect of this layer must have been slight, as pears from which the petals had dropped were frozen to the center.

The fact that the temperature of vegetation may differ from that of the surrounding air at night is well recognized. For example, Garriott and McAdie state, "There are several processes by which the temperatures of plants may be reduced below the temperature of the air which surrounds them. The most important of these processes is radiation. * * * It appears that the temperature of surfaces upon which frost forms and of the air in immediate contact with them is lowered by the evaporation of moisture from the surfaces."[4] Church and Fergusson note, in connection with a table showing temperatures injurious to fruit, "These temperatures are approximately those of the air in contact with the fruit and blossoms. It is quite possible, however, that very delicate measurements would indicate somewhat lower temperatures, due to evaporation from the immediate surfaces of the plants."[5]

In orchard-heating literature it is almost universally assumed that the temperatures of the fruit are the same as the air temperatures.[6] West and Edlefsen state in their bulletin already quoted, "In case of natural freezes in the orchard, where the temperature is falling slowly from sundown till sunrise, there is little doubt that the fruit buds take on the resulting temperature of the surrounding air." The authors just quoted, and Chandler as well, conducted freezing experiments in which they exposed plant tissues to low temperatures in closed chambers where conditions were similar to those prevailing in the orchard on a cloudy, foggy night. Their results may be taken as applying to cases in which the fruit and air temperatures agree, but not when the fruit is cooler than the air.

It seems that an important factor has been neglected or minimized. It is well known that the reading of an unsheltered thermometer is, at times, several degrees lower than that of a similar sheltered instrument; that is, the unsheltered thermometer may be cooled (mainly by radiation) several degrees colder than the surrounding air. Also, the reading of the wet-bulb thermometer, even at the time of the minimum temperature, may be much below the air temperature on account of cooling by evaporation of moisture. The combined effect of radiation and evaporation in reducing the temperature of the fruit surely can not be negligible, therefore. Consider, for example, a blossom, wide open, with tender, succulent, moist organs exposed to the air; surely it is not unreasonable to assume that in extreme cases the vital part, the pistil, is several degrees colder than the air; and that in any case when the sky is clear and the minimum air temperature is much above the dew point a material (and variable) depression of the fruit temperature exists. Such extreme atmospheric conditions are not uncommon in the Grand Valley, and undoubtedly occur frequently in other fruit-growing districts of the arid West. It is clear, therefore, that variations of temperature difference between fruit and the surrounding air should be added to the explanations usually given for variations in damage to fruit by low temperatures.

Since other factors than air temperature affect the amount of damage, it follows that the orchardist who governs his heating operations solely by means of a temperature-damage table and thermometer readings may on some occasions waste fuel and labor by heating too much, while at other times he may lose his crop by not heating with sufficient promptness and vigor. If there be no Weather Bureau station close at hand to give information regarding the atmospheric conditions, the following apparatus would be found useful: A sling psychrometer (wet and dry bulb thermometers) for getting the dew point, or simply a wet-bulb thermometer to determine the cooling effect of evaporation at the time; a thermometer exposed in a shelter and another unsheltered, to find the cooling effect of radiation, roughly; a thermograph to record the rate of temperature fall and the length of time temperature is low. It is customary for orchardists to expose their thermometers unsheltered—combination of sheltered and unsheltered is preferable; but if only one instrument is used, the practice of using it unsheltered is not as open to criticism as is sometimes assumed, since it probably records the actual temperature of the fruit more closely, and is therefore a better indicator of danger than if sheltered. Many meteorological and biological factors, some of which have been indicated above, must be considered in connection with heating the orchard. The final, and most important, question is, of course, "How much additional profit will result from heating?" The answer depends, finally, upon the cost of heating and the price that will be received for the crop saved. Any information regarding damage from freezing will assist in finding the answer.

PREDICTION OF MINIMUM TEMPERATURES.

It is evident that the Weather Bureau should give to fruit growers who heat their orchards the earliest and most definite information possible regarding the approach of low temperatures in order that orchard-heating

[4] "Notes on Frost," by E. B. Garriott, revised July, 1910, by A. G. McAdie, Farmers' Bulletin No. 104, U. S. Department of Agriculture.

[5] "The Avoidance and Prevention of Frost in the Fruit Belts of Nevada," by J. E. Church and S. P. Fergusson, Bulletin No. 79, Agricultural Experiment Station of Nevada, p. 26.

[6] See, however, my notes already referred to.

preparations may be completed. As killing temperatures do not occur every season, some growers who heat small tracts do not fill and distribute their heaters until a warning is issued by the Bureau, and it is a very common practice in the Grand Valley to set filled heaters throughout the orchards, but out of the way, under the trees, each a few steps from the place where it will be fired. For numerous other reasons much work needs to be done after danger is indicated.

OUTLINE OF SYSTEM AT GRAND JUNCTION.

The special forecasting system that has been evolved at Grand Junction is applicable to a single station or to any central station with its surrounding substations. When dangerous temperatures are indicated, a forecast based on the morning weather map and on substation reports is issued as early as practicable. This prediction indicates as closely as may be the probable severity of the coming freeze. In the early afternoon a definite prediction of the minimum temperatures at the several substations is to be made, using as bases maximum temperature and the noon humidity observation at the central station as well as the expected general meteorological conditions the next morning. If at the time of the regular evening observation it appears that the afternoon prediction needs modification, special advices should be given out at that time. A final forecast, based on the evening weather map and on the evening observation at the central station, is made as soon as the evening reports from outside districts can be charted and studied. Special advices regarding the atmospheric humidity, probable duration of damaging temperature, etc., are to be given out when conditions warrant such action.

In a general way the definite minimum temperature forecasts are based on the results obtained and made in accordance with the methods outlined in my paper entitled "Predicting Minimum Temperatures in Grand Valley, Colorado." [7] This paper was largely devoted to extending and applying to Grand Valley conditions the hygrometric formula of J. Warren Smith, which considers the difference between the evening dew point and the ensuing minimum temperature as a rectilinear function of the evening relative humidity under radiation conditions.[8] I showed, among other things, that—

1. Hygrometric observations may be used, not only in predicting minimum temperatures at the station where the observations are made, but also for predicting such temperatures at places many miles away.

2. The minimum-temperature relations between the central station and the substations, and among the substations, vary with certain meteorological elements, especially distribution of atmospheric pressure, cloudiness, and wind velocity. Relations should, therefore, be found for each substation separately for several types or classes of weather conditions. Five classes were used in my investigation, namely:

Class I.—Sky clear; wind velocity less than 10 miles per hour; high-pressure area centered over, or immediately west or northwest of, the district.

Class II.—Sky clear; wind less than 10 miles per hour; high-pressure area centered immediately east or northeast of the district, i. e., just east of the Continental Divide.

Class III.—Sky clear; wind velocity 10 miles per hour, or more.

Class IV.—Sky partly cloudy; wind velocity less than 10 miles per hour.

Class V.—Sky partly cloudy; wind velocity 10 miles or more per hour.

3. Hygrometric minimum temperature relations exist, not only for clear weather but also for partly cloudy.

NOON HYGROMETRIC RELATIONS.

In an unpublished report dated July 11, 1918, I showed that noon hygrometric observations may be used in Smith's rectilinear formula, and give in the Grand Valley practically as accurate results as do the evening observations. Table I, herewith, gives the Smith constants and correlation factors for Class I, computed for the Grand Junction office and for two substations in the Valley, using October data for three years. Both noon and evening observations were used for the purpose of comparison. In two cases the closer relations are shown for the noon readings.

TABLE I.—*Straight-line relation between the dew point and relative humidity at Grand Junction, Colo. (observed in the evening and at about noon), and minimum temperatures the following morning in October, Class I of weather conditions.*

Station.	Observation.	*n*	*r*	*E*	*a*	*b*
Grand Junction (W. B. office)	Noon	32	−0.860	0.029	26.3	−0.562
	Evening	32	− .805	.042	22.4	− .425
Ground exposure (Grand Junction)	Noon	32	− .681	.064	17.9	− .483
	Evening	32	− .788	.045	13.2	− .327
Palisade	Noon	32	− .829	.037	19.2	− .488
	Evening	32	− .637	.071	15.3	− .354

However, I showed, also, that the hygrometric relations are not best indicated by straight lines, at least in this vicinity, in April and October. On figures 1*A* to 5*B*[9], herewith, I have made dot charts showing both noon and evening hygrometric relations for the Grand Junction office and four substations for each of the five weather classes previously used, based on data for the month of April during the five years 1914 to 1918, inclusive. In each case I have drawn free-hand "curves of best fit" for the data, 50 curves in all. I have also drawn the graphs of the straight-line equations that were computed in my previous study referred to for the office data for the four Aprils of 1914 to 1917, inclusive. A cursory examination is sufficient to show that the new

[7] See MONTHLY WEATHER REVIEW, May, 1918, 46:213-228.

[8] Smith, J. Warren, "Predicting Minimum Temperatures." MONTHLY WEATHER REVIEW, August, 1917, 45:402-407.

[9] Only figures 1*A* and 1*B* are reproduced.

curves are not straight lines, but hyperbolic or parabolic; also, confirming the results of Table I, that the noon data give practically as close indications as do the evening data. Table II gives constants of parabolic equations for Class I, all five stations; and Table III similar constants for the Grand Junction office, Classes II to V. Three of the substations considered in this last study are in the Grand Valley at distances from the office varying from about three-fourths mile to 11 miles. The fourth substation, Delta, distant about 36 miles in an air line, is located in the valley of the Gunnison River, which flows into the Grand at Grand Junction. The country between Delta and Grand Junction is generally rolling and of no great elevation, although the Gunnison flows in a canyon much of the distance; the general meteorological conditions are usually practically identical at the two places.

TABLE II.—*Constants of parabolic equations, Class I, April.*

	Noon hygrometric data.			Evening hygrometric data.		
	x	y	z	x	y	z
Grand Junction, office	48.0	−1.5	0.011	38.0	−1.2	0.009
Grand Junction, ground exposure	43.0	−1.52	.011	40.4	−1.65	.015
Orchard Mesa	52.1	−1.48	.011	43.1	−1.78	.016
Palisade	38.6	−1.2	.0084	32.4	−1.08	.008
Delta	26.3	−.82	.0044	24.7	−.95	.007

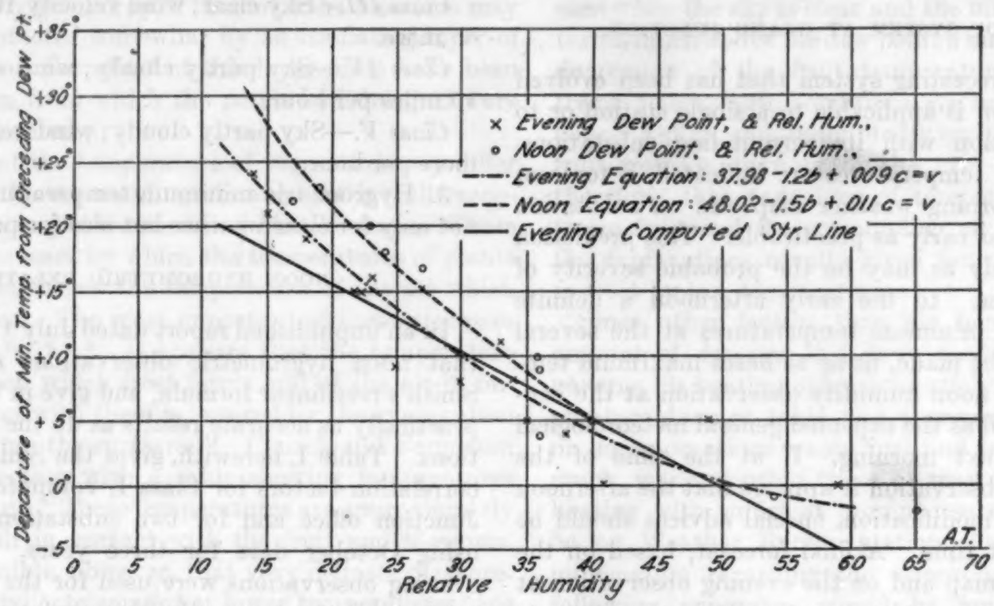

FIG. 1A.—Grand Junction, Colo., Class I, April, 1914–1918. Sky clear; wind velocity less than 10 miles an hour; high-pressure area centered over, or immediately west or northwest of the district. Using evening and noon dew point and relative humidity data.

TABLE III.—*Constants of parabolic equations, Grand Junction office, April, Classes II to V, inclusive.*

	Noon hygrometric data.			Evening hygrometric data.		
	x	y	z	x	y	z
Class II	43.1	−1.55	0.014	54.5	−2.05	0.019
Class III	35.0	−0.71	0	35.0	−0.76	0
Class IV	47.3	−1.63	.014	45.7	−1.61	.014
Class V	75.9	−3.75	.055	54.0	−2.25	.03

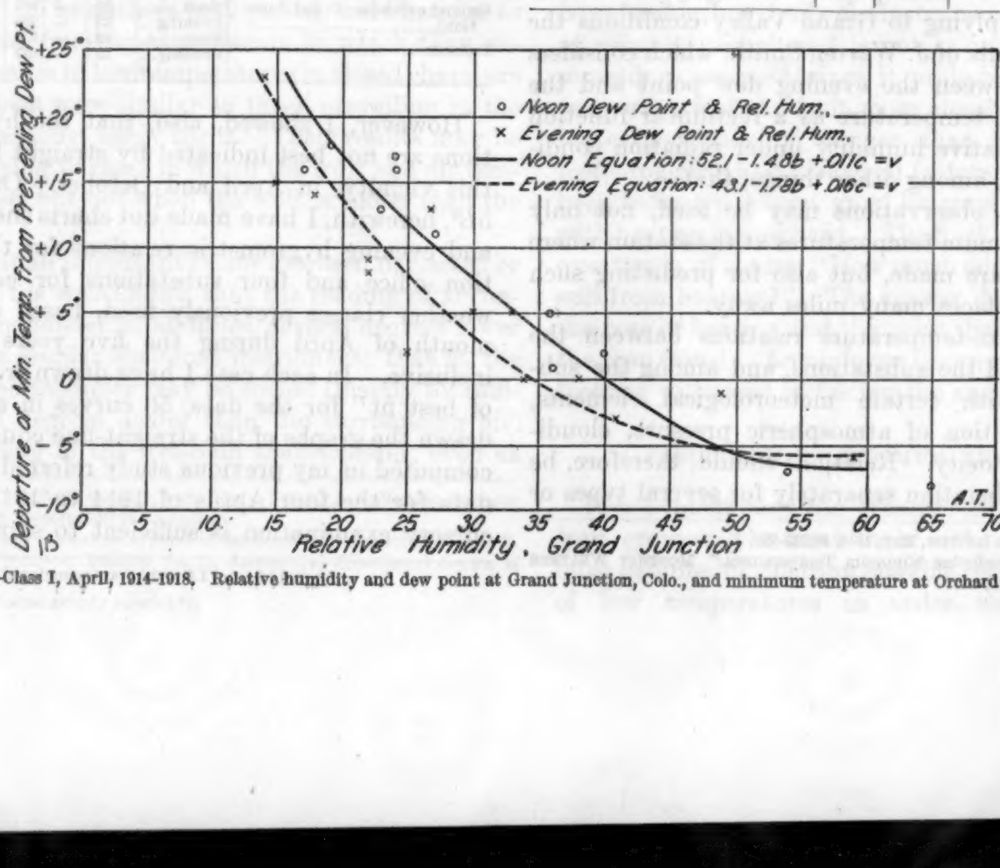

FIG. 1B.—Class I, April, 1914–1918. Relative humidity and dew point at Grand Junction, Colo., and minimum temperature at Orchard Mesa, Colo.

MAXIMUM—MINIMUM TEMPERATURE FORMULA.

I have previously called attention to my early use of another formula, which, for the month of April at Grand Junction, takes the general form

$$Y = \tfrac{5}{8}X + Z,$$

Where X is the maximum temperature, Y is the ensuing minimum temperature, and Z is a variable whose value depends upon the weather conditions during the night. The use of this formula has heretofore been confined to predicting temperatures at the office. A modification of this formula and an extension of its use are now proposed.

On figures 1*Ab* to 5*Bb* [10] I have plotted (and drawn by the eye, free-hand, curves of best fit) the relations

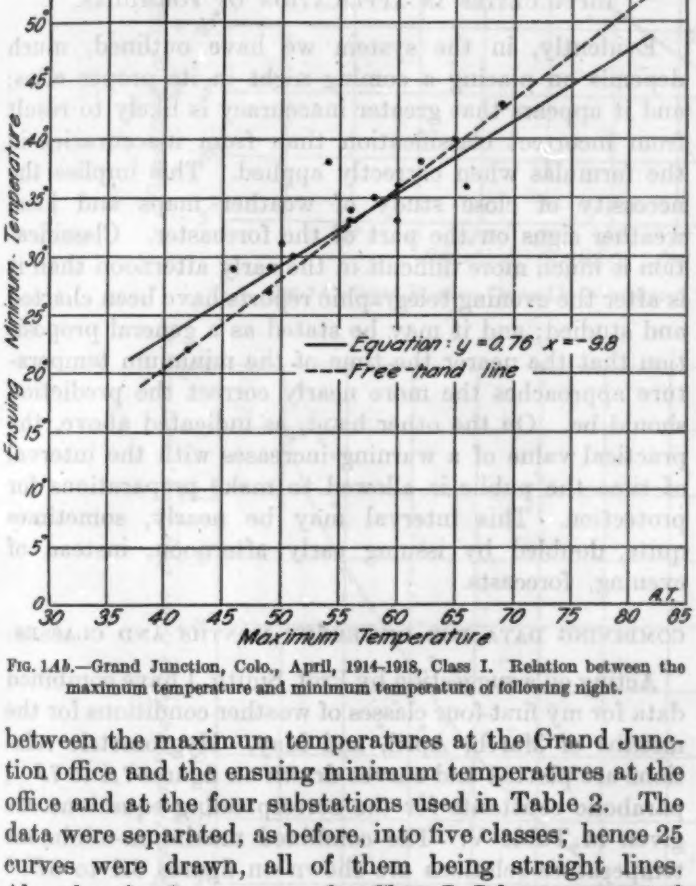

FIG. 1*Ab*.—Grand Junction, Colo., April, 1914-1918, Class I. Relation between the maximum temperature and minimum temperature of following night.

between the maximum temperatures at the Grand Junction office and the ensuing minimum temperatures at the office and at the four substations used in Table 2. The data were separated, as before, into five classes; hence 25 curves were drawn, all of them being straight lines. Also, for the five cases under Class I, I have computed by method of least squares the rectilinear coefficients for the equations best fitting the data, except that Fruitvale, a station in the Grand Valley, is substituted for Delta; results are given in Table IV. In the same table I give also, for purposes of comparison, data for similar equations for the four substations, except that the maximum temperatures used were those recorded at those several substations instead of those that occurred at the Weather Bureau office.

[10] Only figs. 1*Ab* and 1*Bb* are reproduced.

TABLE IV.—*Relation between the maximum temperature and the next morning's minimum temperature, in the Grand Valley, Colo., April (1914–1918): Class I of weather conditions.*

Station.	Using office maximum.				Using own maximum.			
	r	*E*	*a*	*b*	*r*	*E*	*a*	*b*
Grand Junction (W. B. office)	0.908	0.030	−1.38	0.622	......	......	......	......
Grand Junction (ground exposure)	.847	.048	−6.05	.625	0.878	0.039	−11.0	0.660
Palisade	.749	.074	+0.72	.543	.638	.100	+ 6.32	.437
Orchard Mesa	.842	.049	−9.96	.685	.854	.046	−13.7	.714
Fruitvale	.729	.079	−7.06	.638	.715	.082	− 5.61	.590

n=16 in each case.

The equations take the form

$$Y = bX + a$$

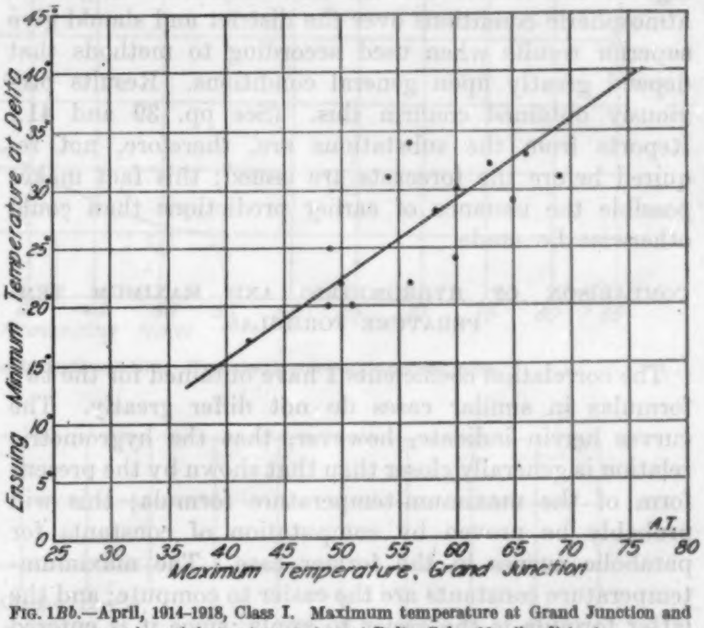

FIG. 1*Bb*.—April, 1914-1918, Class I. Maximum temperature at Grand Junction and ensuing minimum temperature at Delta, Colo., 36 miles distant.

where a and b are constants, X is the maximum temperature, and Y is the ensuing minimum temperature. The Weather Bureau office equation is

$$Y = 0.622\ X - 1.38,$$

which is practically identical with the form previously used. The very high correlation shown in this case explains the success I have had in using the equation in practical forecasting. The relations for the four substations considered are not so close; but they are very good, and are practically the same whether the maxima used are those recorded at the office or at the particular substation, except that Palisade shows somewhat better results with the office maxima. (See page 39).

In my previous work with this formula the influence of the evening dew point was found to be important. Considerable study has failed to show such influence on the data for the five classes now used. However, the additional term, Z, is added provisionally to indi-

cate the possible effect of unknown factor or factors; and we have, for the general form of the formula,

$$Y = bX + a + Z$$

SUBSTATION REPORTS NOT NEEDED IN MAKING FORECASTS BY MEANS OF OUR FORMULAS.

It is evident that the substation morning temperatures depend more upon the general distribution of, and changes in, atmospheric pressure, temperature, humidity, cloudiness, wind, etc., than they do upon variable and local conditions at the substations. As our central station instruments are less affected by variable and local conditions than are those at the substations, the readings of the former are the best indicators of general atmospheric conditions over the district and should give superior results when used according to methods that depend greatly upon general conditions. Results previously obtained confirm this. (See pp. 39 and 41.) Reports from the substations are, therefore, not required before the forecasts are issued; this fact makes possible the issuance of earlier predictions than could otherwise be made.

COMPARISON OF HYGROMETRIC AND MAXIMUM TEMPERATURE FORMULAS.

The correlation coefficients I have obtained for the two formulas in similar cases do not differ greatly. The curves herein indicate, however, that the hygrometric relation is generally closer than that shown by the present form of the maximum-temperature formula; this will probably be proven by computation of constants for parabolic curves in the former case. The maximum-temperature constants are the easier to compute; and the latter formula is the easier to apply, since it is entered immediately with the maximum and gives a direct value for the minimum. It is hoped that a value for the Z term may be derived in the near future. Apparently the two formulas can be used with advantage to supplement each other, as suggested above.

USE OF GRAPHS IN FORECASTING.

In actual forecast work with either formula, most of the labor of computation may be avoided by the use of graphs, instead of the equations themselves. (See my paper referred to above.) In fact, the labor of computing constants of the equations may be avoided entirely by using dot charts and drawing the graphs free-hand, as has been done herein. The free-hand curves are, perhaps, not quite as accurate as the computed equations, but the errors will be slight, *if there be a close relation between the function and its argument.* For example, for four cases under Class I, maximum-temperature formula, I have drawn graphs of the computed equations *after* the free-hand curves were entered; it appears that no material increase in accuracy of the forecasts will result from the computations. Also, my original value of the maximum-temperature equation for Grand Junction was obtained from a line drawn according to eye estimate. The free-hand method is particularly useful in selecting the form of curve that best fits the data in cases when time for investigation is limited and in cases where the investigator has a limited mathematical education; also, it has the advantage of showing, not only the average dependence that may be placed on results throughout the whole region of observation (as is the case when the usual computations are made), but, by variations in the scattering of the dots in different regions, roughly what dependence may be placed on different portions of the curve.

DIFFICULTIES IN APPLICATION OF FORMULAS.

Evidently, in the system we have outlined, much depends on placing a coming night in its proper class; and it appears that greater inaccuracy is likely to result from incorrect classification than from inaccuracies in the formulas when correctly applied. This implies the necessity of close study of weather maps and local weather signs on the part of the forecaster. Classification is much more difficult in the early afternoon than it is after the evening telegraphic reports have been charted and studied; and it may be stated as a general proposition that the nearer the time of the minimum temperature approaches the more nearly correct the prediction should be. On the other hand, as indicated above, the practical value of a warning increases with the interval of time the public is allowed to make preparations for protection. This interval may be nearly, sometimes quite, doubled by issuing early afternoon, instead of evening, forecasts.

COMBINING DATA FOR DIFFERENT MONTHS AND CLASSES.

Acting on a suggestion by Prof. Smith, I have combined data for my first four classes of weather conditions for the months of March, April, and May. Hygrometric relations are plotted and curves drawn on figures 7*A* to 7*J* [11]; parabolic constants for the corresponding equations are given in Table V. The combined maximum-minimum temperature relations are shown on figures 6*A* to 6*E* [11] and in Table VI. For the three spring months we have, for each station, three "combined" curves applicable to practically all clear and partly cloudy mornings with light winds. On account of scarcity of available data for some of the classified charts, the combinations give nearly as good results as the former, and are much more convenient.

[11] Only figs. 7*A*, 7*E*, 7*I*, 6*A*, and 6*D* are reproduced.

Grand Junction, Colo.

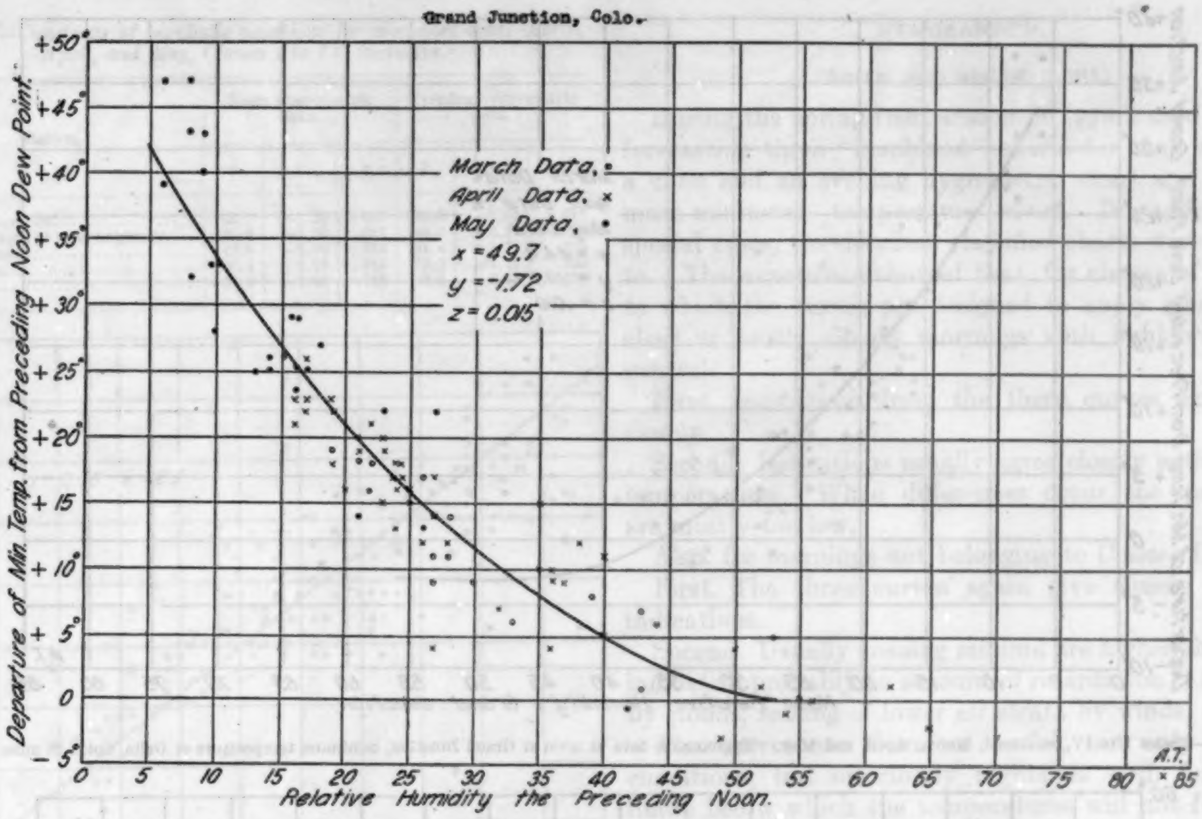

FIG. 7A.—Grand Junction, Classes I to IV combined, March, April, and May. Hygrometric observation taken at noon.

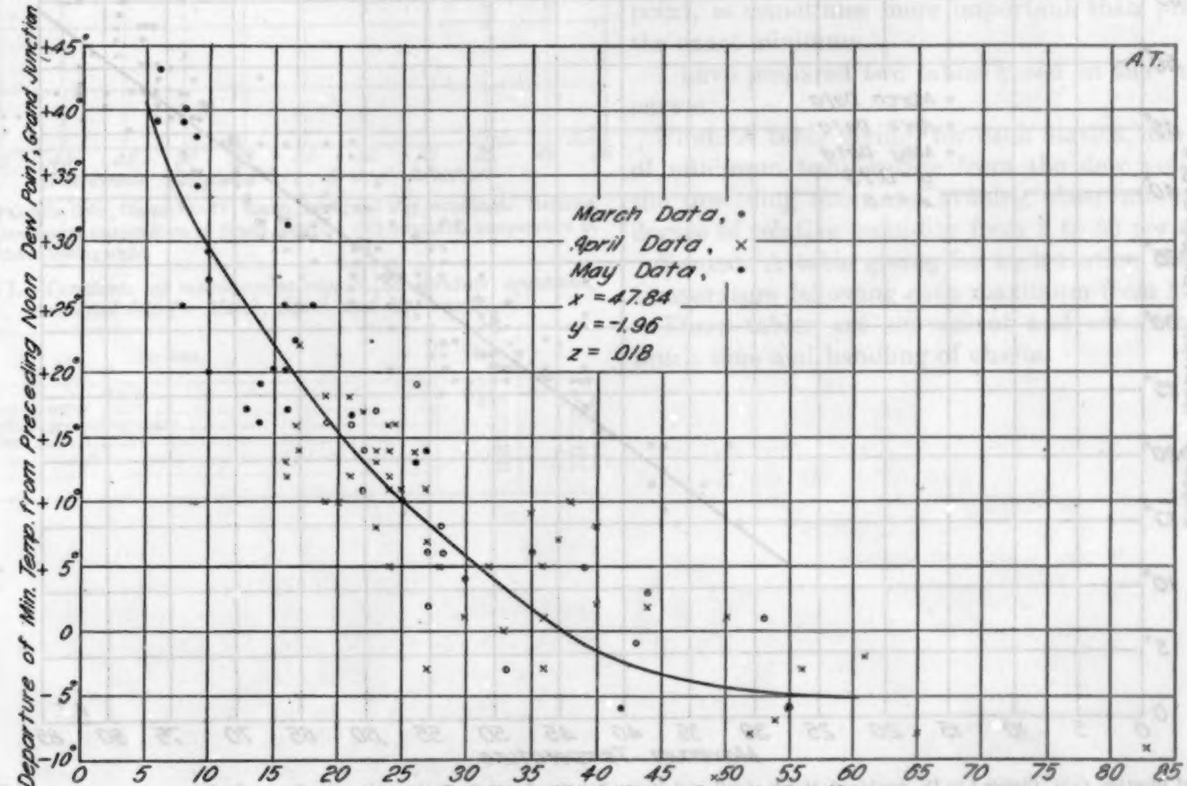

FIG. 7B.—Classes I to IV combined, March, April, and May. Hygrometric observation at noon at Grand Junction, minimum temperature the following night at Orchard Mesa, Colo.

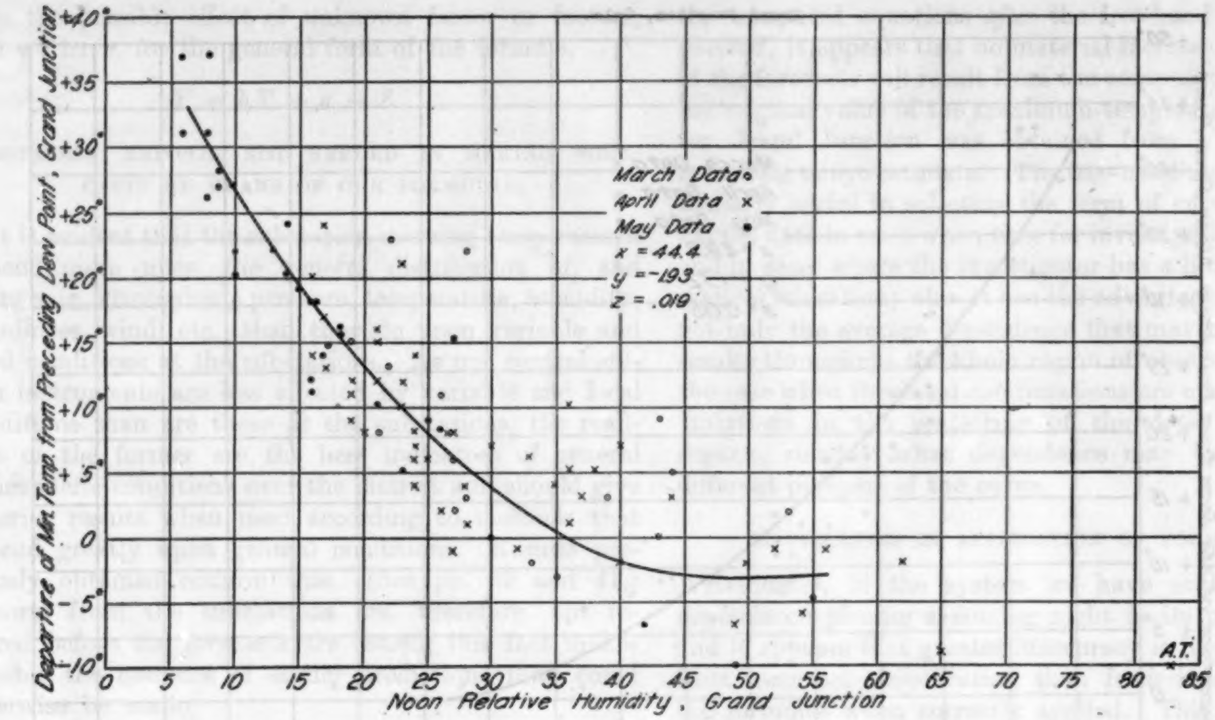

FIG. 7I.—Classes I to IV, combined, March, April, and May. Hygrometric data at noon at Grand Junction, minimum temperature at Delta, Colo., 36 miles distant.

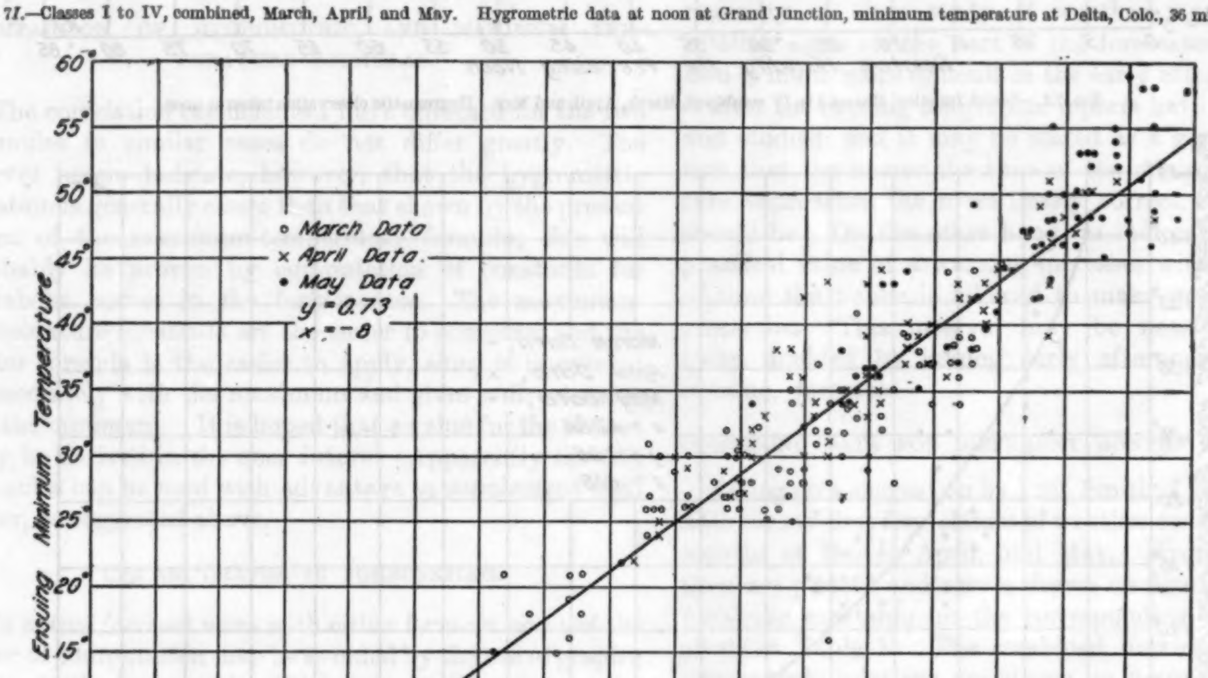

FIG. 6A.—Grand Junction, Colo., Classes I to IV, combined, March, April, and May. Relation between maximum temperature and minimum temperature of following night.

TABLE V.—*Constants of parabolic equations for combined data, March, April, and May, Classes I to IV, inclusive.*

Station.	Noon hygrometric data.			Evening hygrometric data.		
	x	y	z	x	y	z
Grand Junction, office	49.7	−1.72	0.015	48.6	−1.83	0.017
Grand Junction, ground exposure	45.9	−1.86	.017	46.6	−2.1	.022
Orchard Mesa	47.8	−1.96	.018	41.4	−1.7	.016
Palisade	47.4	−1.75	.015	50.2	−2.16	.022
Delta	44.4	−1.93	.019	46.1	−2.13	.021

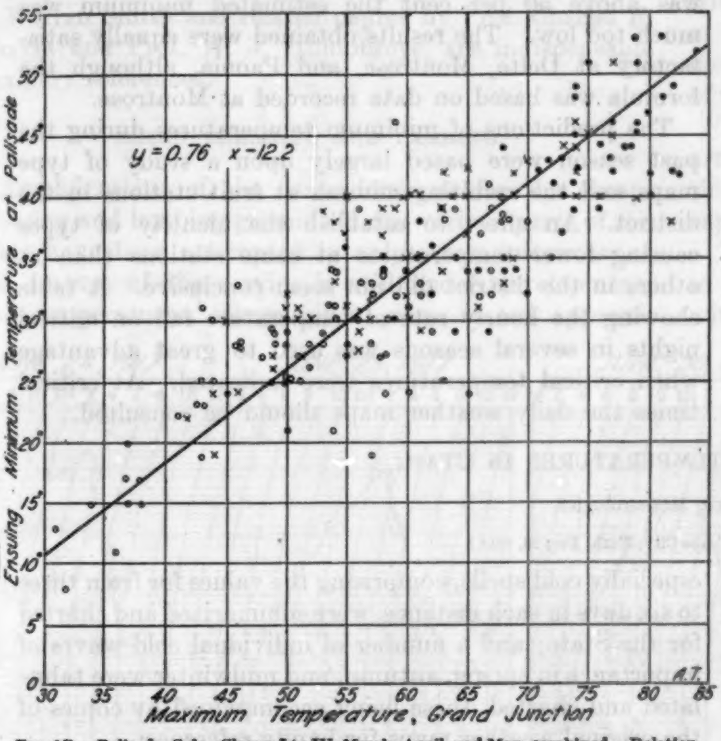

FIG. 6D.—Palisade, Colo., Classes I to IV, March, April, and May, combined. Relation between maximum temperature at Grand Junction and minimum temperature at Palisade the following night.

TABLE VI.—*Constants of maximum-minimum temperature equations, combined data for March, April, and May used.*

Station.	b	a
Grand Junction, office	0.73	− 8.0
Grand Junction, ground exposure	.71	−12.1
Orchard Mesa	.81	−17.8
Palisade	.76	−12.2
Delta	.72	−14.5

MEMORANDUM.

(Based on report dated July 18, 1919.)

During the spring frost season of 1919 I used in daily forecasting three "combined" charts for each station—a noon and an evening hygrometric chart and a maximum-minimum temperature chart. In addition, in special cases, the detailed, classified charts were referred to. The experience showed that, for classes of weather to which the curves are designed to apply (that is, for clear or partly cloudy mornings with light winds), in general:

First. Indications from the three curves agree very closely.

Second. Indications usually agree closely with ensuing temperatures. When differences occur the indications are mostly too low.

Also, for mornings not belonging to Classes I to IV—

First. The three curves again give closely agreeing indications.

Second. Usually ensuing minima are higher than those indicated, probably on account of retardation of radiation by clouds, mixing of lower air strata by winds, etc.

The curves are therefore useful, not only in ideal conditions, but on cloudy nights as well, for setting limits below which the temperatures will not fall. The setting of such lower limit, especially if it be the freezing point, is sometimes more important than prediction of the exact minimum.

I have prepared two tables based on the "combined" curves:

First. A table giving, for each station, the departure of minimum temperature from the dew point at both the preceding noon and evening observations, for each degree of relative humidity from 5 to 80 per cent.

Second. A table giving for each station the minimum temperature following each maximum from 30° upward.

These tables are convenient and accurate and save much time and handling of charts.

PREDICTION OF MINIMUM TEMPERATURES IN THE GUNNISON AND UNCOMPAHGRE VALLEYS IN WESTERN COLORADO BASED ON DATA RECORDED AT MONTROSE.

By Frederick W. Brist, Meteorologist.

[Dated: Denver, Colo., Jan. 11, 1919.]

The topography of the fruit districts in the Gunnison and Uncompahgre Valleys on the western slope in Colorado is very uneven. * * * The district lies in a vast basin having a slope to the westward. It is bounded on the north by the Grand Mesa, with an elevation of 10,000 feet; on the east by the West Elk Mountains; on the southeast by the Continental Divide; and on the southwest by the Uncompahgre Plateau, in elevation ranging from 9,000 to 10,000 feet. The north fork of the Gunnison River flows in a southwesterly direction, through Paonia, to its junction with the Gunnison, about midway between Paonia and Delta, while the Uncompahgre River flows in a northwesterly direction, through Montrose to Delta, where it joins the Gunnison River.

The preparation of a hygrometric formula has been hampered by the lack of dry-bulb and wet-bulb readings. * * * The values obtained from the use of the formula, when combined and averaged with those obtained from the use of the average range (from maximum to following minimum) and the temperature at the median temperature hour, were found to be quite dependable, except when the relative humidity was somewhat above 50 per cent. When the relative humidity was above 50 per cent the estimated minimum was much too low. The results obtained were equally satisfactory at Delta, Montrose, and Paonia, although the formula was based on data recorded at Montrose.

The predictions of minimum temperatures during the past season were based largely upon a study of type maps and the resulting minima at fruit stations in the district. An effort to establish the identity of types causing lower temperatures at some stations than at others in the district did not seem conclusive. A table showing the hourly rate of temperature fall on critical nights in several seasons was used to great advantage when critical temperatures were indicated. At critical times the daily weather maps should be consulted.

FORECASTING MINIMUM TEMPERATURES IN UTAH.

By J. Cecil Alter, Meteorologist.

[Dated: Weather Bureau, Salt Lake City, Utah, Dec. 26, 1918.]

The amplification of the Utah State forecasts for sheep shearing and lambing and fruit-raising interests in spring; alfalfa seed, tomato, and vegetable interests in autumn; and shippers of perishable products and users of stream flow for hydroelectric purposes in winter, and occasional miscellaneous purposes, are based on ordinary studies of substation temperatures, the daily weather map, and the files of same.

Practically all amplifications are issued in the morning, because of the nature of the interests served, and the protection practiced; hence the specific temperatures stated, when temperatures are mentioned, have a somewhat wider range than is customary in the use of formulae and other devices for 10 or 12 hour (evening) forecasts, being usually from 3° to 6° in spring and autumn and from 5° to 10° in winter.

HELPFUL COMPILATIONS.

The relation of minimum temperatures at substations during important cold snaps in the seasons in question to the daily weather map has been sought in some detail in all past records at substations located in or near the sheep-shearing, lambing, fruit, alfalfa seed, tomato, hydro-electric, and shipping regions.

Tables of averages with geographical charts showing the values for the State, reduced approximately to the same period of time, have been prepared by pairing substation records separately with those for Salt Lake City in identical months and years. Tables of minima in all especially cold spells, comprising the values for from three to six days in each instance, were summarized and charted for the State; and a number of individual cold waves of importance in spring, autumn, and midwinter were tabulated and charted, these being accompanied by copies of the original weather maps for handy reference.

The tendency of cloudiness to become local or general in certain kinds of maps, and the resultant effect on the minima of the State, were shown briefly by a series of tables; and some general relations of afternoon maxima to the following minima have also been sought by tables and charts, showing especially the first and second day temperature falls from maximum to minimum and the first and second day falls from minimum to minimum at the inception of cold spells.

An appendix of notes for each seasonal study has also proven helpful. These are usually merely ideas written down at the time of the original study, or later, and are not necessarily precepts or rules. One reference table under this last head cites all definitely characteristic weather maps meeting such specifications as "Caused rain or snow in northern Utah only," "Caused rains of unusual duration," "Caused a general drop in temperature, delayed one day in southern portion," "Temperature drop sharp in western portion only;" there being 12 or 14 such specifications used as appropriate. The notes and some of the tables are added to occasionally, and all the original papers are kept in separate packages at the forecast table for convenience.

Supplements Nos. 1 and 4 to the MONTHLY WEATHER REVIEW, "Types of storms of the United States, and Their Average Movements," and "Types of Anticyclones of the United States and Their Average Movements," by Mr. Edward H. Bowie and Mr. R. Hanson Weightman; and the volume "Weather Forecasting in the United States," by the supervising and the district forecasters, are indispensable manuals; and articles on forecasting in the MONTHLY WEATHER REVIEW, especially those concerning minimum-temperature predictions by Prof. J. Warren Smith and related papers by Prof. Charles F. Marvin and Prof. W. J. Humphreys, are indispensable auxiliary references.

SHEEP SHEARING AND LAMBING.

Amplifications of the State forecasts for the sheep-shearing and lambing grounds in the various parts of the State have been attempted in only a few instances, as this feature of the service is still under development. The temperatures, where given, were stated approximately within 5° or 6° to oral inquirers to whom additional information was given concerning conditions on the map.

Most of this service is handled by the district forecaster using the State forecasts with a suffix, "Notify stockmen," these being issued to special addresses when precipitation is expected with temperatures in the lower forties or lower, when temperatures are expected to reach the upper thirties or lower without precipitation, and when fair weather is indicated for a day or sc with temperatures in the middle forties or higher.

The amplifications are attempted on this same basis on special request, there being no regular addresses receiving the amplifications at present. Last season, which was the first in which this service had attention in many districts, certain local railroad officials made a few requests for forecasts for shearing points on their line, giving us the temperatures reported by their agents; there may be further development along this line in future.

Two or three hours after the peak in the afternoon curve (soon after sunset) there is normally a reversal of

FRUIT-FROST FORECASTS.

Frost fighting with fire has almost disappeared from Utah, only two neighbors on Provo Bench remaining, who smudge faithfully. One of them is the special meteorological observer, and he reports weather and temperatures daily to this office in season. He has access by telephone to the daily State forecasts, but when temperatures are expected to fall close to or below freezing, an amplification is issued from this office stating within from 3° to 5° the probable minimum temperature at his station, or qualifying the temperature trend predicted in the State forecast for his station with mention of frost, if expected.

The morning forecasts are desired so that smudging arrangements can be made, though additional information is sent in the evening if conditions are changing rapidly.

There is an interesting if not useful feature presented in the Provo Bench thermograph trace in connection with minum'um temperature predictions. (See fig. 1.)

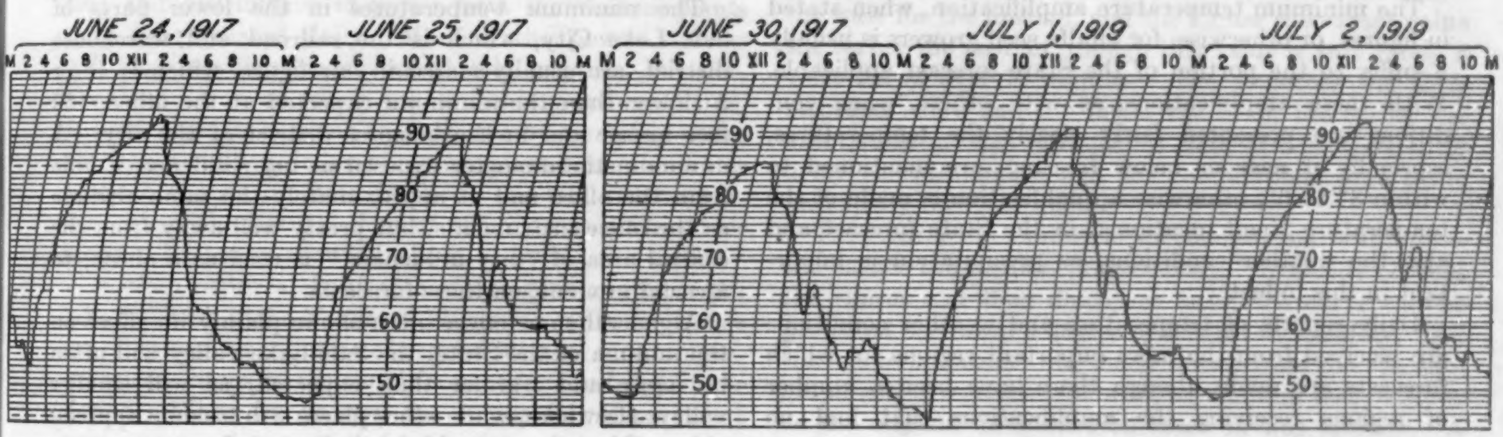

FIG. 1.—Thermograph trace at Provo Bench, Utah, June 24, 25, and 30, 1917, and July 1 and 2, 1919.

the temperature trend, or a 10° or 12° rise abruptly in from 15 to 75 minutes, the beginning of which is usually quite sudden. This may possibly have some relationship with the filling of the valley with cold air, though since it occurs so early in the evening, and the station is about 500 feet above Utah Lake, the phenomenon is more probably due to the mixing of the air over the bench lands by a simple canyon or mountain breeze which begins at that time.

The amount of this sudden rise in temperature varies, but does not appear to have any important relation to the amount of subsequent fall; and it is usual for one or two additional overturnings to occur before morning, none of which seem greatly to shorten the downward sweep of the nocturnal curve with any certainty or system in the records available.

A certain amount of promise lay in the occasional absence of the phenomenon, in which case it might have been expected that the radiation curve, with all irregularities smoothed out, would run definitely to a lower minimum. In fact, in the few instances noted in a short record of about a year, the absence of the disrup-

tion in the curve actually did show slightly greater ranges from maximum to subsequent minimum than on adjacent nights with the overturning feature present. However, on other nights, some distance away, in the records, there has been almost as great a range with the irregularities present.

This reversal of temperature trend on the thermograph curve is absent when a LOW is charted over the middle and northern Rocky Mountains, and a HIGH over the middle Pacific coast or farther inland, giving a backing gradient against the canyon or mountain slope wind from the Wasatch Mountains, which stand immediately to the east of Provo Bench lands. Such a map, however, is in itself a caution to the forecaster, and is at hand nearly 12 hours earlier than the thermograph curve. Thermograph traces for Provo Bench from June 24 to July 2, 1917, are shown herewith, and attention is invited to the down curve on the night of June 24.

ALFALFA-SEED WARNINGS.

The minimum temperature amplification, when stated in figures, or otherwise, for alfalfa seed growers is usually a suffix to the portion of the State forecast applicable. With these amplifications, as with others, when conditions are presented fairly clearly the temperatures, especially if near or below freezing, are mentioned to within 3° to 6°, otherwise a qualification is made of the temperature trend mentioned in the State forecast and also the weather conditions, as precipitation is important in this industry.

Daily reports of temperature and weather conditions are received from the more important regions for which forecasts are made, though there have been a number of regions receiving the amplifications that had no weather stations or reports.

Where practicable, the alfalfa field stations have been in shelters placed on the ground; that is, on supports just off the ground, in the alfalfa foliage. In one such region a cooperative station is about a mile distant from the alfalfa field station, at the same altitude and same general exposure, manned by the same observer, giving a fairly good comparison.

The minima in this alfalfa field average 3° or 4° lower than at the cooperative station, though a complex variation is often noted, and it is in this lower strata that the alfalfa crop, usually less than 18 inches high, is located. [On the 10th of September, 1918, the cooperative station minimum was 37°, and the alfalfa field 33° with no damage; September 19, cooperative station 36° and alfalfa field 32°, with no damage; September 20, cooperative station 37°, alfalfa field, 30°, from which considerable damage was found at thrashing time; and September 25, cooperative station 37° and alfalfa field 34° and no harm noted.] These inconstancies in the alfalfa field are doubtless due to atmospheric moisture, and humidity observations will be undertakn if any protective measures are ever taken for standing alfalfa. At present the only protection is to cut and windrow or pile the crop that is nearly ripe. Thermograph studies will probably be made, beginning next season, in quest of radiation information.

SHIPPERS' FORECASTS.

Shippers' forecasts appear on the daily weather card in winter, from first freezing tempeartures in autumn to last in spring, approximately, and are intended to cover a one-night journey by freight or express train out of Salt Lake City, through a rather wide variation of exposures. All forecasts are made to harmonize with the State forecasts, as being amplifications of same, so far as conditions herein stated will warrant. The compilation of temperatures at substations has seemed to warrant making these forecasts to within a limit of 5° or 6°, or as great as 10° when near or below zero. However, no telegraphic reports are received from the more critical mountain localities prior to making the forecasts and the amplifications are doubtless inconsistent in some instances.

The minimum temperatures in the lower parts of Salt Lake City, which is the railroad and warehouse district, are usually stated in one figure, which is 4° or 5° lower than the minimum expected at the office, 160 feet higher and in the business district of the city. A minimum thermometer exposed at my residence, a mile from the office and at approximately the same altitude as the office instruments, but pretty well away from the central area of "city influences," is used as a check, to a certain extent, on these forecasts.

A general snow cover often shows plainly its effect on the minima of the State; the Salt Lake valley will often be foggy and warmer than expected, as will smaller valleys elsewhere, while other places will become appreciably colder than would be indicated by type maps, temperature averages, and other aids.

The higher portions of the railroad lines through the Wasatch Mountains are from 10° to 18° colder than Salt Lake City, while the colder parts of the roads running westward average from only 8° to 14° colder. However, on quiet nights, with a HIGH immediately over northern Utah, the crest of the Wasatch will average easily 20° colder than Salt Lake City; the higher the barometer, and the lower the temperature (say, below 20°), the greater is the depression or difference, reaching 30° at times over important areas.

The temperatures at Salt Lake City (and Ogden) and the Wasatch crest region are nearly alike, whatever the value, when strong winds prevail as a result of the nearness of a LOW center of considerable intensity. It is usual to note a difference greater than the average when a HIGH overspreads Wyoming, which reaches to the Wasatch range. Such a HIGH, if large and well defined, will often show colder weather at Salt Lake City than over western Utah and eastern Nevada. Western Utah has also shown the abnormality of warmer weather than Salt Lake City when a LOW, slipping over the crest of the Rocky Mountains in Wyoming, causes

a sharp temperature drop at Salt Lake City. Cold winds always drain through the westerly canyons into the settlements close up against the western foot of the Wasatch from a large HIGH over Wyoming, especially if there is a LOW to the southwest.

FORECASTS FOR HYDROELECTRIC WORKS.

Estimates of temperatures in northern Utah and southeastern Idaho are made each morning in winter for the engineering department of the Utah Power & Light Co., a corporation which supplies much of the light and power in both States. These are made in much the same manner as are the shippers' forecasts, though we often have the advantage of minimum temperature reports and sky conditions from six or eight power plants in the district reported by telephone through the company's main offices here. Pocatello serves very well as a sort of key station.

These forecasts are used by the company to anticipate the closing of streams by ice or slush, so that the operation and distribution of power from the various plants may be regulated daily. Most of the power streams will close up tight in sustained cold weather, but one, the Bear River, on which are several large power plants, is kept open in extreme emergencies by pumping water through a million-dollar pumping plant from the water beneath the ice on Bear Lake, on the Utah-Idaho border, when the natural flow of the river is stiffened or stopped by heavy snowfall, slush, or by ice.

It often requires about 48 hours to get water from the lake to Grace, Idaho, the nearest large power plant. Hence we often add an estimate of general weather and temperature conditions to the usual forecast for the full 48-hour period. When we do not, the engineering department uses our weather reports from points as far distant as the north Pacific coast and makes its own 48-hour estimates roughly. [Maj. Cooper Anderson, who has this work in general charge, has done some very good work along this line, though it has fallen to several other men at times, and they seem very glad to accept our estimates when given.]

PREDICTING BY MEDIAN TEMPERATURE.

The following is from a report on the frost-warning service in Rogue River Valley, Oreg., for the spring of 1916, when I had local charge of the work at Medford.

An examination of all available thermograph records at Medford, Oreg., for some years, and the compilation of certain data for all nights showing symmetrical temperature drops, gave some more or less reliable median temperature data.

The time from which the median was reckoned was the beginning of the definite evening drop at the moment the sun disappeared behind the low mountains, regardless of the maximum time or value. An effort to associate a definite lapse of time for the median with certain approximate values of the sunset temperature was unsatisfactory, probably for lack of a sufficient number of observations.

The results of the study showed: March, for 48 observations, the median temperature averaged 3 hours and 41 minutes after the beginning of the drop at sunset; in April, for 31 observations, the median occurred 3 hours and 31 minutes after sunset; and in May, for 31 observations, the median was 3 hours and 22 minutes after sunset. The individual variations in the column of data from the means given above are in some instances considerable, and make forecasting from the median somewhat uncertain at times, yet the median temperature observation was used to good advantage this season; in fact, since the median occurs rather late in the evening by the use of the sunset reckoning, an interpolated value obtained by extending this curve from an earlier observation was in a few instances the cause of a good decision in making a forecast.

MEDIAN TEMPERATURE NOTES.

From the limited amount of data at hand (three years) the following notes were made in addition to the values given above: The lower the sunset temperature the longer the wait for the median, and the higher the sunset value the earlier the median, though this value is very rarely a variation of over 10 minutes. The smoother the thermograph curve and the faster the drop, the earlier the occurrence of the median. A few clouds apparently delay the median, though the compilations were made principally for clear nights.

The greater the number of successive clear, warm days the earlier the median progressively. If clouds obscure the sunset and then disappear later, the curve can be projected backward a degree or so with some safety. All time determinations are made direct from the thermograph sheet, regardless of whether running fast or slow, as the original data were obtained in this manner. A small paper scale was used to note time on the sheet. A falling humidity appears to delay the median and a rising humidity seems from data at hand to advance the median, probably as much as 15 minutes or more (a degree or so) at times.

GENERAL REMARKS.

In general, it is probably safe to consider that the definiteness or precision with which minimum temperature forecasts are stated may vary with the definiteness and dependability of the determination of the temperatures at which the interests served will suffer; and, in addition, in the case of frost fighting with fire, a limiting factor is the accuracy with which temperatures over the area under consideration can be equably controlled.

The forecaster should also see that thermometer readings by which his forecasts are verified are correctly made—the thermometers correctly calibrated, exposed, and read, especially in orchard-heating work. The small louvered shelter for a single thermometer which we introduced in the Rogue River Valley in the spring of 1916 and the educational work done in thermometer calibrating, reading, and exposing did much to increase the apparent verification of the forecast amplifications.

PREDICTING MINIMUM TEMPERATURES IN THE WALLA WALLA, WASH., FROST-WARNING DISTRICT.

By Charles C. Garrett, Meteorologist.

[Dated Weather Bureau, Walla Walla, Wash. Dec. 28, 1918.]

A local frost-warning district was started, with Walla Walla as the center, in the spring of 1915. It was the first attempt to localize systematically the district warnings of frost and low temperature for the benefit of the orchardists and truck gardeners in various districts of southeastern Washington and northeastern Oregon. A "key station," with ground exposure for the instruments, was established in the residence section of Walla Walla and substations at a number of points within the district. The instrumental equipment at each of these stations consists of maximum and minimum thermometers, sling psychrometer, and rain gage. Thermographs are installed at the "key station" and two of the substations.

The problem of predicting minimum temperatures in the vicinity of Walla Walla presents difficulties that are peculiar to certain mountain valleys of the West and are absent to a great degree in the plains region and central valleys. While the use of the daily weather map is essential and should be the basis for temperature forecasting, it can not be relied upon alone by a forecaster situated in a region where local topographic conditions have much to do in modifying changes of temperature.

Most of the older orchard districts in this region, particularly those in the immediate vicinity of Walla Walla and surrounding Milton and Freewater, Oreg., at the foothills of the Blue Mountains, have always been quite free from severe frost damage. A total loss of the fruit crop in those districts has never occurred and severe freezes during the critical period in spring, with exception of those of apricots and early peaches, are very rare. For that reason the growers have not been very much interested in methods of orchard heating and have been slow to investigate the possibilities of frost prevention.

The near immunity from severe frost damage of the greater part of the orchard acreage in the Walla Walla district is due in large part to the effect of dynamic heating. A striking feature of the climate of the Walla Walla valley and neighboring valleys is the local chinook wind. This wind is quite common in the winter season particularly, but "chinook effects" are apparent in all seasons. A chain of the Blue Mountains extends southwest to northeast of the valley and when the barometric distribution is favorable, viz, an area of low pressure off the northern Washington coast or over British Columbia and an area of high pressure overlying the plateau region to the south or southeast, the air that is drawn from the high altitudes toward the region of low pressure is heated dynamically as it descends to the relatively low altitudes of the Walla Walla basin. Pronounced chinook conditions are rare outside the winter season because the plateau area of high pressure does not remain any length of time, except in winter; but as the winds of this region are from a southerly direction about 65 per cent of the time, during the three spring months, descending the mountain slopes, there is often an appreciable heating effect even when this region is covered by an area of high pressure. Very often there will be a rapid fall in temperature during the first part of the night, when the wind will be blowing from a northerly or westerly point, but toward morning the normal wind shift to southerly results in a retardation of the nocturnal fall, perhaps causing a rise in temperature.

In some of the newer fruit districts of southeastern Washington and northeastern Oregon, where orchards have been started during the last six or eight years, the climatic conditions are not so favorable as regards freedom from damaging frosts. For that reason more interest has been taken in the question of smudging or heating by the growers in those districts, and quite a number have at different times experimented with various methods. It was largely in the interest of those orchardists that the local warning district was established. It must be said, however, that interest in frost protection in those districts has decreased in the last few years. This is due partly to the fact that recent seasons have been quite free from severe freezes during the blossoming period, but for the most part the falling off can be attributed to the unsatisfactory economic condition of the commercial fruit industry. When fruit growers do not do well financially the tendency is, of course, to lower expenses in every way possible. The orchardists believe that it does not pay to equip their orchards with oil pots and buy oil when they are not sure to be able to market their crops to advantage.

The study of methods of predicting minimum temperatures should, however, be carried on wherever possible even though not much practical use may be made of the warnings locally. The knowledge gained by the forecaster may prove to be of considerable value to other forecasters in regions where extensive and systematic efforts are made to combat injury to fruit bloom and other tender vegetation. Also the local situation may change in such a way that the demand for accurate predictions of minimum temperatures during critical times in the spring or fall will increase. In such case the forecaster can draw upon the results of his studies and experience.

Some investigators in the past have laid considerable emphasis on the value of evening dew-point readings in determining the probable morning minimum temperature. Although there is at times a close agreement between the two values, yet the relationship is so indefinite and variable, often under apparently similar night conditions, that it can not be relied upon for practical fore-

casting. But it has been found that if the relative humidity be considered as well as the dew point, good results can be had. During the last two seasons (1917 and 1918) a modified form of the "Donnel formula" has been employed by the writer with fairly good success. The formula had been used by Wells, at Boise, and is expressed as follows:

T = expected minimum temperature.
H = relative humidity at 6 p. m.
D = dew point at 6 p. m.

Then, $T = D - \frac{H-40}{4}$.

As stated by Wells, it is well known that the condensation of moisture sets free energy which becomes manifest as heat, hence the formation of dew or frost retards the nocturnal fall in temperature. It should be borne in mind, however, that it only retards the fall, but does not check it altogether. If the dew point is slightly below the current temperature at the time of evening observation; in other words, if the relative humidity is high, the dew point will be reached early in the night, provided conditions are favorable for radiation. Hence on such nights the retarding effect of the formation of dew or frost will not be sufficient to offset the long period of radiation, and the temperature will fall considerably below the dew point. If, on the other hand, the dew point at observation time is far below the current temperature; in other words, if the relative humidity is low, there will not ordinarily be time for the temperature to fall quite to the dew point before morning. The value representing the relative humidity merely forms the most convenient expression of the relation between the current temperature and the temperature of the dew point.

The formula given is merely a convenient way of saying that if the relative humidity at Walla Walla is above 40 per cent at 6 p. m. the temperature will fall below the dew point 1° for every 4 per cent the dew point is above 40°; and if it is below 40 per cent the minimum will be above the dew point 1° for every 4 per cent the relative humidity is below 40°.

In reports covering the work of the Walla Walla frost-warning district for the seasons of 1917 and 1918 tables were prepared to show the results of the application of the Donnel formula to the data of the "key station" for 17 nights in 1917 and 29 nights in 1918. In preparing the tables only the nights under anticyclonic control were included, when the weather was mostly clear and conditions generally favorable for morning frost. No attempt was made to subclassify the nights according to different positions of the high-pressure areas, different local wind directions, or other climatic factors. On the 46 nights during the two seasons the actual recorded minimum temperature was the same as the minimum estimated by use of the formula on 5 nights, higher than the estimated on 25 nights, and lower than the estimated on 16 nights. The variation between the actual and estimated minimum on the 16 nights when the estimated was too high was never more than 4°, and was 2° or less on 11 of the nights. On the 25 nights when the estimated minimum was too low the variation was 4° or less 15 times. When the difference was more than 4° it was nearly always clearly due to the nocturnal fall being retarded by increased cloudiness during the night or by local dynamic heating. The application of the formula to the data of the different substations gives similar results where accurate psychrometric observations were taken. The results seem to show that the Donnel formula is useful in this locality for predicting fairly closely the lowest temperature that may be expected if local conditions, such as dynamic heating or increased night cloudiness, do not retard the normal night temperature fall. For more accurate predictions of the morning minimum, however, other factors need to be taken into account in using the formula. Some study has been made at this station with a view to separating the nights into subgroups acccording to different barometric distribution, or into wind direction groups, with the intention of modifying the formula to suit different conditions, but so far no very satisfactory results have been reached.

Another system for predicting the minimum temperature in this locality has been tried by the writer, namely, the median temperature method. Explanation of the method used for determining the time of median temperature, or halfway point in the temperature fall between the maximum of one day and the minimum of the next morning, was fully explained by Prof. J. Warren Smith in the MONTHLY WEATHER REVIEW for October, 1914. The average median time for this station on clear or mostly clear nights, as determined from thermograph records during the last three frost seasons, is 8:15 p. m. But it is found that the median time is later as the season advances, ranging from 7:40 p. m. for the last half of March to 8:25 p. m. for the last half of May. The use of this method for estimating the minimum temperature for the same 46 nights that have been discussed in connection with the Donnel formula gave results as follows: The actual minimum was the same as the estimated minimum on 5 nights, higher than the estimated on 24 nights, and lower on 17 nights. The greatest plus difference (estimated higher than actual) was 9° and the greatest minus difference was 9°. The variation between estimated and actual minimum was 4° or less on 29 of the 46 nights. On the 17 nights when the minimum was estimated too high the difference exceeded 4° but 5 times.

A comparison of the minima estimated by the Donnel formula with those estimated by the median time method shows that while on some dates the variation of estimated from actual minimum, deduced by the two different methods, are in quite close accord, on the other hand, a rather wide divergence is noted on a number of dates. By

averaging the minimums estimated by each of the two methods quite good results are secured. By this method the difference between estimated and actual minimum was 3° or less on 33 of the 46 nights. The estimated minimum was never more than 4° too high. It was from 4° to 7° too low on 10 nights.

While the effect of the mountain influence in tending to modify night temperatures complicates the problem of predicting minimum temperatures, the error in the predictions, due to this influence, is on the safe side; that is, the estimated minimum will be too low rather than too high. While it is desirable to be able to estimate the minimum as closely as possible, a formula that can be relied upon to estimate closely the lowest temperature that will occur provided no retarding influence interferes is of value without question. To predict a temperature much higher than actually occurs is a grievous error in frost forecasting.

From the studies that have been made at Walla Walla of the two methods herein discussed, as well as of other systems, the following conclusions have been reached: Any formulated method for estimating the morning minimum is of value only on clear or mostly clear nights, and even on such nights the forecaster should not follow it blindly for best results but must have regard for other factors taken in their proper relation. This requires a long and careful study of local climatic conditions. The Donnel formula is based on correct principles. Both the Donnel formula and the median time method are of valued aid when used in connection with the weather map. The use of the Donnel formula gives slightly better results in this district than that of the median time method. Averaging the minimums estimated by each of the two methods gives better results on the whole than either of the two used alone.

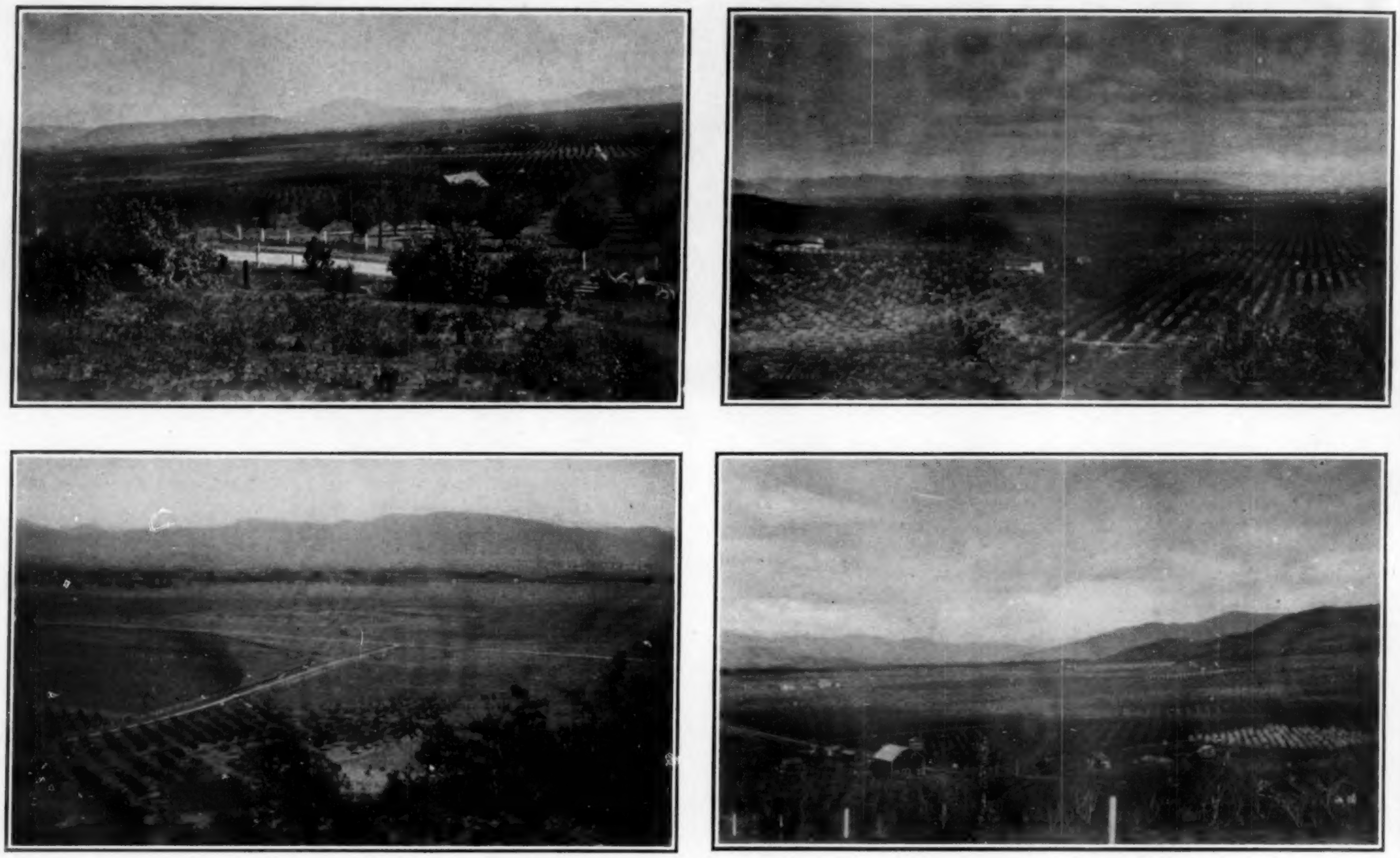

FIG. 6.—Views of Rogue River Valley near Medford, Oreg., showing topography.

FIG. 7.—Views of Pomona Valley, Calif., from summit of San Jose Hills.

FORECASTING MINIMUM TEMPERATURES IN OREGON AND CALIFORNIA.

By FLOYD D. YOUNG, Observer.

[Dated: Pomona, Calif., Jan. 28, 1919.]

INTRODUCTION.

The issuing of forecasts of frost for the benefit of agricultural interests has long been an important detail in the work of the Weather Bureau. Until recently, however, except in a few small districts, these forecasts have been based almost entirely on the weather maps and have been issued in general terms, such as "light frost," "heavy frost," and "killing frost."

While forecasts of this character are of great value to fruit and truck growers in general, they have proved to be not entirely satisfactory in localities where protection against frost is practised on a large scale and at great expense. This is due to the fact that on a given night different portions of a single valley may experience temperatures varying all the way from light to killing frosts. This is especially true in the Pomona Valley and no doubt throughout the remainder of the Great Valley of southern California.

In the Pomona district the average difference between minimum temperatures registered in the colder and warmer portions of the valley floor is about 6°, and differences between minimum temperatures at stations in the valley and on the hillsides amount to 25° at times.

The same condition prevails in the Rogue River Valley, in southern Oregon, although differences there are not so great.

A more important reason why orchardists desire more detailed information than that contained in the general frost forecasts is the fact that it is much easier to hold the temperature at a given point by firing than to raise it after it has fallen below the danger point. In the Pomona district if a minimum temperature of 26° or lower is expected, firing is begun at 28° or 29°, whereas if the lowest temperature expected during the night is above 26°, only a few heaters are lighted just before sunrise.

Another detail of considerable importance is the forecasting of the time when the temperature will reach a given point during the night. This has not yet been fully developed, but experiments in the Rogue River Valley have shown it is possible to make such forecasts with reasonable accuracy and improvement along this line is only a matter of additional study.

METHODS OF MAKING AND DISTRIBUTING MINIMUM TEMPERATURE FORECASTS.

It has been the custom for several years to detail an official of the Weather Bureau to the Rogue River Valley during the frost season with headquarters at Medford, Oreg., to handle the frost-warning service in that district. A similar service has recently been inaugurated in the Pomona Valley, in southern California, in connection with investigations in orchard heating being conducted there. Estimates of the expected minimum temperature at the key station are made each night at the district forecast center, based on the 5 p. m. (Pacific time) weather charts and on observational data telegraphed from the station for which the estimates are made. These forecasts are telegraphed to the official in the fruit district, generally before 7 p. m. The local official amplifies the forecast to apply to other parts of the district and also has authority to modify the estimate for the key station if this seems desirable.

This paper will deal only with the local aspects of the problem; a discussion of the types of pressure distribution that cause frosts in the two districts will not be attempted. It is not desired to give the impression that forecasts made at the district forecast center are not of great value or that local forecasts are often made without regard to the district estimate. In the writer's opinion, no one method of forecasting minimum temperatures should be followed blindly, but every item of information available should be used.

DEVELOPMENT OF HYGROMETRIC FORMULA.

In 1912, Mr. Charles A. Donnel, then stationed at Boise, Idaho, developed the following formula for estimating the minimum temperature for the following morning, using data secured at 6 p. m. local standard time:

$$\text{Minimum} = \text{dewpoint} - \frac{\text{Relative humidity} - 40}{4}$$

This was used as an aid in forecasting minimum temperatures on clear nights at Boise for several years afterward.

During the spring of 1917 the writer was detailed to conduct the frost-warning service in the Rogue River Valley, and in an attempt to improve the accuracy of the minimum temperature forecasts the above-mentioned formula was tested for that locality. The work done by Prof. Smith[1] along the same lines had not come to the attention of the writer at that time.

No 6 p. m. observations had been taken at Medford, but observations had been made at 5 p. m. for several years, and an attempt was made to modify the formula so that the data secured at the 5 p. m. observation could be used.

In the Boise district the formula had been used only when the weather was clear all night; in the Rogue River Valley so many damaging temperatures occur after nights with cloudy or partly cloudy weather until 7 p. m. or later, it was necessary to modify the formula to

[1] Smith, J. Warren, Predicting Minimum Temperatures, MONTHLY WEATHER REVIEW, August, 1917, 45; p. 402; also historical note by Prof. Marvin.

make it applicable to conditions of this kind. It was found that the form noted above gave fairly accurate results with 5 p. m. data at Medford when the weather was cloudy at the time of observation, but cleared later in the evening. On nights when the sky was partly cloudy (0.4 to 0.7) the best results were obtained when the constant to be subtracted from the relative humidity was changed to 30, and when the weather was clear the constant 20 most nearly applied.

These changes in the value of this quantity simply serve to lower the estimated minimum when radiation from the earth is uninterrupted after the occurrence of the maximum temperature, and to raise it when cooling by radiation is decreased or prevented entirely by clouds during the early part of the night.

After the original formula had been thus modified it was found that quite accurate results were obtained on radiation nights when the dew point at 5 p. m. lay anywhere between 30° and 40°. When the dew point was above 40° or below 30° the results obtained were considerably in error, the forecast minimum being too low on nights when the dew point was low and too high when the dew point was high. At the same time it was noted that on all nights with the same 5 p. m. dew point the minimum indicated by the formula required practically the same correction to bring it into agreement with the minimum actually recorded on the following morning.

By studying data accumulated in preceding seasons a series of corrections to be applied to the results obtained by using the straight-line formula were worked out for all the different values of the dew point encountered, and gaps were filled by interpolation. Additional corrections to results by formula were found necessary when the relative humidity was above 67 per cent. The formulas as they have been used at Medford are given below, together with corrections to be applied with varying values of the dew point and relative humidity. R, relative humidity; D, dew point at regular evening observation (between 4:40 p. m. and 4:50 p. m.); T, minimum temperature indicated for the next morning; V, variable quantity, depending on the temperature of the dew point; V', variable quantity, depending on relative humidity.

Weather at time of observation.

Clear.......................... $T=D-\frac{H-20}{4}+V+V'$

Partly cloudy.......................... $T=D-\frac{H-30}{4}+V+V'$

Cloudy.......................... $T=D-\frac{H-40}{4}+V+V'$

Dew point (degrees):	V	Relative humidity (per cent):	V'
Below 26..........	+10	Below 68..........	0
26 to 29..........	+ 1	68 to 72..........	+1
30 to 40..........	0	73 to 75..........	+2
41 to 45..........	− 3	76 to 78..........	+3
Above 45..........	− 6	Above 79..........	+4

These corrections (V and V') are listed just as they were first worked out in 1917. As additional data are gathered during later frost seasons, it will probably be possible to make changes that will increase the accuracy of the results, especially as some of the back observational data are not entirely dependable.

Assuming that all nights on which minimum temperatures below 35° occurred were radiation nights, and including the data for all such nights, the results obtained by applying the formulas and corrections to new data obtained during the latter part of the 1917 season and during the 1918 season, including all nights on which the minimum temperature fell below 35°, will be found in Table 1.

TABLE 1.—*Application of hygrometric formula to new data at Medford, Oreg., 1917 and 1918, including all dates with minimum temperature below 35° F.*

Date.	Dew point.	Relative humidity.	Weather.	Forecast, minimum.	Actual minimum.
1917.		*Per cent.*		° *F.*	° *F.*
Apr. 3..........	36	46	Cloudy..........	34	33
5..........	35	40	Clear..........	30	31
7..........	40	50	Cloudy..........	35	34
11..........	31	39	Partly cloudy..........	29	31
13..........	42	80	Raining..........	33	32
14..........	34	84	Cloudy..........	27	30
15..........	22	35	Partly cloudy..........	31	32
17..........	31	39	.....do..........	29	29
28..........	22	21	.....do..........	34	34
May 1..........	31	33	Clear..........	28	32
3..........	37	39	.....do..........	32	33
15..........	42	93	Rain..........	30	30
1918.					
Apr. 1..........	31	42	Partly cloudy..........	28	27.7
2..........	26	31	.....do..........	*27	22.0
3..........	14	17	Clear..........	25	25.0
4..........	20	18	.....do..........	30	30.2
12..........	38	92	Cloudy..........	30	32.0
14..........	31	45	.....do..........	30	29.7
16..........	42	56	Partly cloudy..........	32	31.6
17..........	38	34	.....do..........	37	32.9
22..........	30	19	Clear..........	30	34.1
25..........	26	24	.....do..........	26	30.0
26..........	21	15	.....do..........	32	30.9
27..........	22	13	.....do..........	34	33.0
May 4..........	44	58	Cloudy..........	36	34.9
5..........	34	30	Clear..........	32	32.9

*Four-tenths strato-cumulus clouds recorded at observation, but sky cleared entirely within 30 minutes. Forecast using form for clear weather, 24°.

It will be seen that forecasts by the method outlined are reasonably accurate; in fact, they are more accurate in general than forecasts made for the same station, using only the data contained on the evening weather chart, together with information as to the dew point at 5 p. m.

USE OF FORMULA AT POMONA, CALIF.

No psychrometric observations had been made at Pomona prior to November, 1917, when the making of minimum temperature forecasts for that district was begun. However, it was found that formulas and corrections developed from 10 years' record at San Jose, Calif., after being modified slightly, gave fairly good results at Pomona. At the end of the season enough data had been gathered to make possible the development of an entire list of corrections for the Pomona key station. The formulas and corrections are given below.

Weather at time of observation.

Clear or partly cloudy . . . . $T=D-\frac{H-25}{4}+V+V^1$

Cloudy . . . . $T=D-\frac{H-30}{4}+V+V^1$

Dew point (degrees):	V	Relative humidity (per cent):	V^1
14	+14	55 to 59	+ 1
15	+12	60 to 64	+ 2
16	+10	65 to 70	+ 3
17 to 19	+ 8	71 and 72	+ 4
20 to 22	+ 7	73 to 88	+ 5
23	+ 6	89 to 93	+ 6
24	+ 5		
25	+ 4		
26	+ 3		
27	+ 2		
28 to 30	+ 1		
31 to 33	0		
34 to 36	− 1		
37	− 2		
38	− 3		
39 to 42	− 4		
43	− 5		
44	− 6		
45 and 46	− 7		
47	− 8		
48 and 49	− 9		
50	−10		
51	−12		
52	−14		

TABLE 2.—*Application of hygrometric formula to new data at Pomona, Calif., 1918–19, to date, including all dates with minimum temperature below 34° F.*

Date.	Dew point.	Relative humidity.	Weather, 5 p. m.	Forecast minimum.	Actual minimum.
		Per cent.		° *F.*	° *F.*
Nov. 25	31	44	Clear	26	32.0
27	42	81	Cloudy	30	31.3
28	33	63	Dusty	26	28.0
29	33	52	Clear	26	29.8
Dec. 1	40	55	do	30	29.3
4	42	51	do	32	33.0
7	47	94	Raining	30	33.0
9	48	92	Clear	28	30.8
10	42	74	do	31	33.3
12	45	76	Partly cloudy	30	30.8
13	41	64	Clear	29	33.0
14	44	66	do	31	32.9
15	44	68	do	30	32.8
16	42	75	do	30	30.0
18	40	60	do	28	30.0
19	45	78	do	30	33.3
21	42	80	Cloudy	30	29.0
22	39	67	Clear	28	27.3
23	39	77	do	27	26.6
24	32	65	do	25	25.4
25	29	60	do	23	25.3
26	30	50	do	25	28.0
27	31	39	do	28	28.2
28	32	35	do	30	27.3
29	46	81	Raining	*31	*22.0
30	28	68	Clear	21	23.2
31	21	45	do	23	22.7
Jan. 1	26	48	do	23	24.0
2	26	45	do	24	26.6
3	25	29	do	28	28.0
4	28	32	do	27	29.8
5	25	25	Partly cloudy	29	25.1
6	27	28	Clear	28	25.2
7	26	27	do	28	26.0
11	47	64	do	31	30.3
12	39	49	do	29	28.4
13	18	18	do	28	24.7
14	20	20	Cloudy	†30	†25.9
15	23	24	do	31	31.3
16	33	40	Clear	29	29.0
17	34	36	Partly cloudy	30	30.9
22	39	35	Clear	32	33.1

* Low minimum due to importation of cold air. (See fig. 4.)
† Only very high thin cirro-stratus present. Actual forecast 28°.

The key station at Pomona is in one of the colder parts of the valley, and as any temperature above 28° is not considered dangerous to any crop grown during the winter months, it is not necessary to consider dates on which the minimum temperature was above 33°. Results obtained by applying the formulas to entirely new data during the 1918–19 season to date are given in Table 2.

The results at Pomona are not so accurate in general as those at Medford, but it is safe to say that when the forecasts for the entire season are considered, those made by formula are more accurate than estimates from type maps alone. Forecasts by formula are usually available at 5 p. m., while forecasts by type maps can seldom be made before 6:30 p. m.

FACTORS WHICH DETERMINE MINIMUM TEMPERATURE REPRESENTED IN HYGROMETRIC FORMULA.

All the more important of the factors that, taken collectively, fix the point to which the temperature at a given spot will fall during the night are included in the following:

1. Rate of effective radiation from the earth during the night, which at any given instant is mainly dependent upon the condition of the sky, the temperature of the radiating surface, and the absolute humidity.
2. Location of station with regard to surrounding topography.
3. Effects of night winds in preventing inversions of temperature and in raising surface temperature after inversion has been built up through mixing of surface air with warmer air above.
4. Temperature of the dew point and probability of its being reached.
5. Importation of warmer or colder air from outside localities.

All these are important in both the Medford and Pomona districts, although those outlined in paragraphs 2 and 3 are considerably more important at Pomona than at Medford on account of the greater nocturnal inversions of temperature at Pomona.

Directly or indirectly, more of these factors are represented in the hygrometric formula than in any other single method of minimum temperature forecasting. The formula states that following nights with the same dew point and relative humidity at 5 p. m. the minimum temperatures will be the same. However, it is apparent that in the association of these two values, factors 1 and 4 are directly represented and factors 2 and 5 are indirectly represented.

Allowance is made for the influence of the absolute humidity on the rate of effective radiation by the use of the dew point. The probability of the dew point being reached during the night, with consequent slowing of the rate of fall in temperature through the liberation of latent heat, is determined by the value of the relative humidity;

if the relative humidity is high, the difference between the current temperature and the temperature of the dew point is small, and vice versa. The combination of the

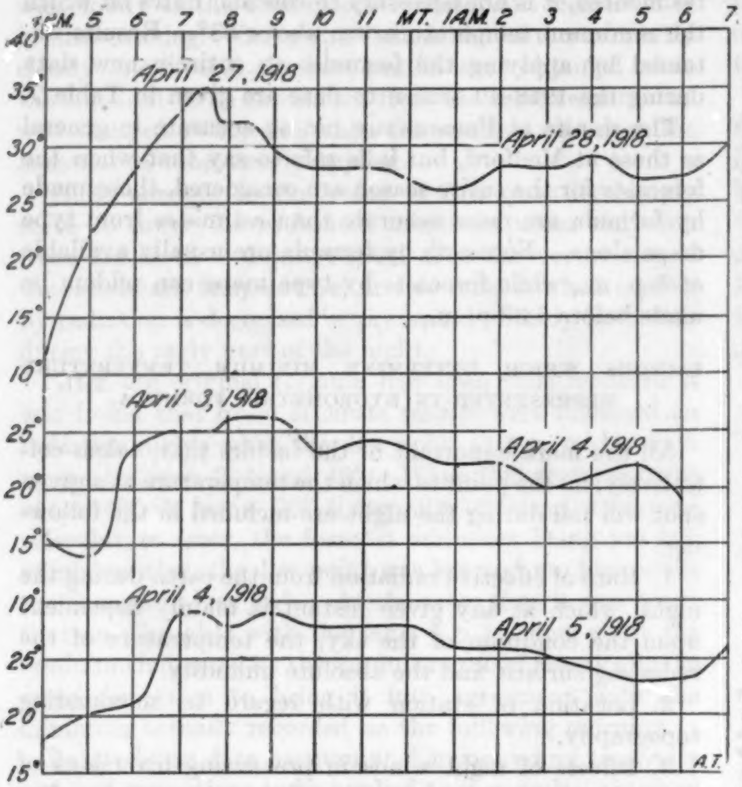

FIG. 1.—Normal changes in dew point at Medford, Oreg., during nights on which the dew point at 5 p. m. is below 26°. Note general similarity of curves.

dew point and relative humidity in the equation gives a value for the current temperature at the time of observation.

Recent studies of nocturnal fluctuations in dew point at Medford indicate that the values of the dew point and relative humidity at 5 p. m. tend to classify the weather during the night; that is, under conditions favorable for frost, if the dew point and relative humidity at 5 p. m. on a given afternoon are the same as the dew point and relative humidity recorded at 5 p. m. on some previous afternoon, changes in the different meteorological elements are likely to be the same on both nights.

When the weather conditions under which a frost forms are considered, the reason why this should be true on most nights is apparent. At both Medford and Pomona a frosty night is generally preceded by a day with cold wind, from a northerly or easterly direction, which dies out in the evening, about 5 or 6 p. m. After that time the only surface air movement is that caused by the cold air draining down the valley floor. Like causes produce like results; if the initial conditions are the same, there is no reason why the minimum temperature should not be the same.

To illustrate this similarity, curves representing fluctuations in the temperature of the dew point at the Medford station on several nights during April and May, 1918, are reproduced in figures 1 and 2. It will be noted that in every case there is a steady rise in dew point from 5 p. m. up to between 7 and 8 p. m., after which there is a slow decline until about the time of sunrise.

On nights when the dew point at 5 p. m. is below 26° the rise in dew point early in the evening is much more rapid than when the dew point at observation is above 26°. This seems to be due to the fact that on practically every night when the dew point is below 26° at 5 p. m. a high-pressure area is located somewhere to the northeastward, causing cold, dry northeasterly or easterly winds from the dry eastern Oregon plains during the day. The slope of the valley is from south to north, and when the air on the valley floor cools in the evening its natural tendency to flow northward down the slope is opposed to the northerly winds, due to general pressure distribution. The result is a gradual falling off of the northerly wind, followed by a few moments of almost complete calm and a change to a slow drift from a southerly direction. The rapid rise in dew point occurs with the decrease in velocity of the northerly wind and the change to southerly.

These rises in dew point indicate an actual increase in the moisture content of the surface air, which undoubtedly has a tendency to retard the rate of cooling at the time when the temperature is falling most rapidly. The large positive corrections to be applied to minimum temperature estimates by formula at Medford when the dew point is below 26° can be partly accounted for in this way.

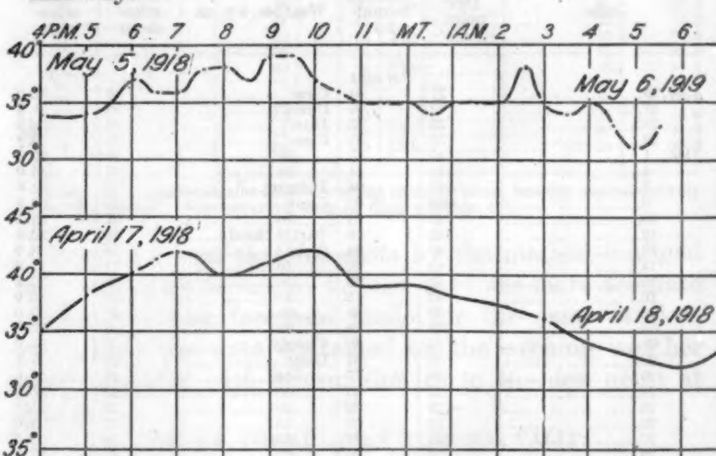

FIG. 2.—Normal changes in dew point at Medford, Oreg., during nights on which the dew point at 5 p. m. is above 25°. Note general similarity of curves and compare with figure 1.

USE OF THE FORMULA IN THE FIELD.

The data in Tables 1 and 2 show that by the use of the formula alone reasonably accurate forecasts can be made at 5 p. m. However, the local forecaster should not be content with these results. The formula indi-

cates what the minimum temperature will be if the changes that take place during the night are what we may term "normal," and a study of the additional data at hand, such as the trend of the barometer, information as to changes taking place in the direction and velocity of the wind, whether the absolute humidity is increasing or decreasing, the actual amount and type of clouds, etc., will generally enable one to make allowance for any unusual influences present.

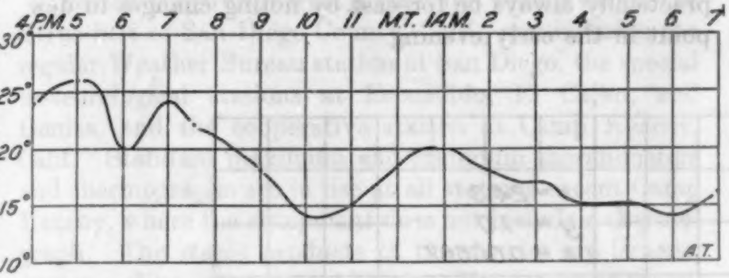

FIG. 3.—Changes in dew point at Medford, Oreg., during a night with importation of cold air. Compare with graphs in figures 1 and 2.

The two most important disturbing factors are the occurrence of wind during the night and the importation of cold air from outside the valley. The former is of much greater importance at Pomona than at Medford, and the latter is about equally important in both districts.

Nocturnal winds always raise the temperature, making the forecast too low, and the importation of cold air lowers the temperature and makes the forecast too high. The only method of forecasting night winds is through a study of the weather map, though the barograph trace sometimes gives advance information of their occurrence. The fruit growers are always ready to excuse an occasional forecast that is too low, but if the estimate on a single night is too high the benefits of the accurate forecasts of an entire season may be nullified.

The importation of cold air during the night is practically always accompanied by a rapid fall in dew point after the 5 p. m. observation instead of the usual rise, and a few dew-point observations in the early evening are usually sufficient to show the forecaster that he has to deal with such a condition. The behavior of the dew point on such nights is shown in figures 3 and 4.

The Weather Bureau rule for determining the condition of the sky at the time of observation has been observed in noting the character of the weather in Tables 1 and 2. It is well known that the higher cirrus or cirrostratus clouds decrease the rate of nocturnal radiation from the earth to only a slight degree. In actual practice, therefore, it is generally safe to use the equation for fair weather when the sky is overcast with clouds of this type at the time of observation and the formation of lower clouds before morning is not indicated.

Storm centers generally pass so close to the station at Medford during the spring months that cirrus or cirrostratus clouds at 5 p. m. are followed by lower clouds later in the evening. Pomona is situated so far to the south, however, that cirrus clouds may persist for days without any lower clouds when a cyclone is passing eastward over northern California.

The writer has found it very helpful at both Medford and Pomona to keep as detailed a record as practicable of the weather during the entire 24 hours of each day during the frost season.

USE OF FORMULA BY LAYMEN.

The question has been raised as to whether the formula can be used to advantage by individual farmers or fruit growers in isolated districts to give them advance information of the occurrence of damaging temperatures.

During the first two weeks in May, 1918, Mr. E. W. Carlton, a prominent fruit grower of Central Point, Oreg., used the formula and corrections as they had been developed for the key station at Medford to estimate the minimum temperature at his ranch, which is several miles from Medford and in an entirely different air-drainage basin. Table 3 shows the results obtained.

TABLE 3.—*Forecasts by hygrometric formula at Carlton Ranch, near Central Point, Oreg.*

Date.	Dew point.	Relative humidity.	Weather.	Forecast minimum.	Actual minimum.
1918.		*Per cent.*		° *F.*	° *F.*
May 2	36	22	Partly cloudy	38	39
3	41	34	do	37	35
4	41	49	Clear	31	30
5	33	29	do	31	30.5
6	39	29	do	37	33
7	38	32	Partly cloudy	35	36
8	36	56	Raining	32	41
9	40	73	Foggy	34	33
10	44	48	Clear	34	33
11	38	27	do	36	37
13	34	39	Cloudy	34	40
14	38	48	do	36	40
15	41	49	do	36	41

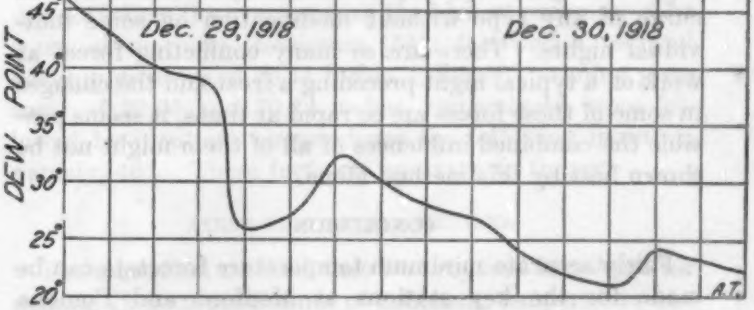

FIG. 4.—Changes in the temperature of the dew point at Pomona, Calif., on the night of December 29-30, 1918. On December 29 the weather was cloudy and threatening all day. Heavy, black squalls drifted over the valley, with heavy showers in the mountains. A trace of rain fell at the key station in the valley from 4 p. m. to 5 p. m. About 8 p. m. the sky cleared suddenly and the temperature fell steadily to a minimum of 24.9° at 7:30 a. m. at the point where the above record was obtained. The key station minimum was 22°. The temperature of the dew point remained from 5° to 10° below the current temperature until toward morning, falling at about the same rate as the air temperature. There was a steady drift of the air from an easterly direction all night, but wind strong enough to rustle the leaves was noted only once during the night and lasted only about 10 minutes.

The test was made on all nights, regardless of whether or not they were radiation nights. The forecast minimum naturally was much too low on nights, such as May 8, when there was a strong wind and the sky was overcast practically all night.

The record is too short to be of much value in showing what can be expected in the long run, but with the exception of the 6th, the forecasts were reasonably accurate on radiation nights.

RELATION OF PARABOLIC CURVE TO POMONA DATA.

In figure 5 the variation of the minimum temperature from the evening dew point has been plotted against the evening relative humidity and a parabolic curve applied to the data as suggested by Prof. Smith.

While the results obtained by using the parabola are much more accurate than with the old straight-line equation, they are not so accurate in general as those obtained through the use of the method of arbitrary corrections.

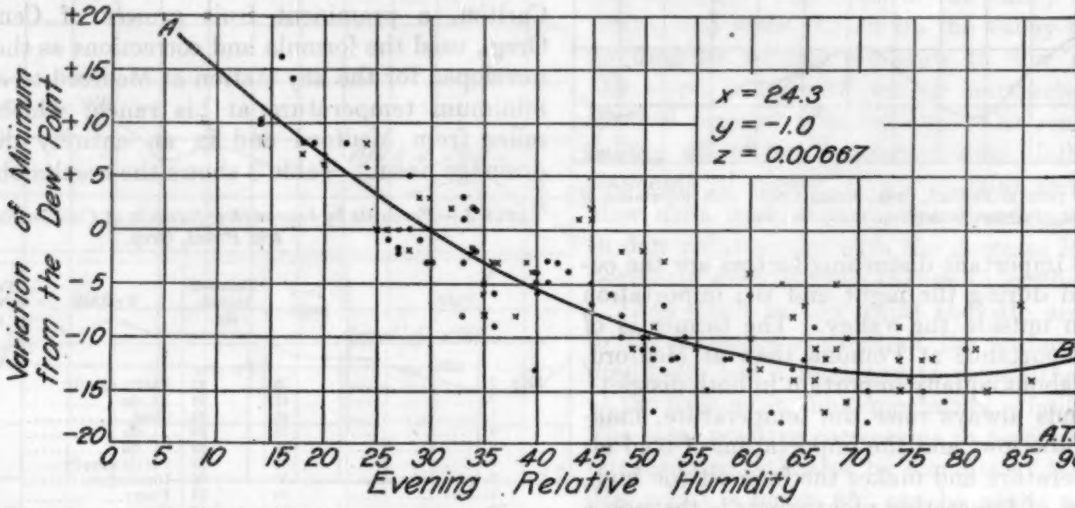

FIG. 5.—Relation between the 5 p. m. relative humidity and the variation of the minimum temperature of following morning from the 5 p. m. dew point at Pomona, Calif. Dots represent 1917–18 data, crosses 1918–19 data. Equation for parabola suggested by Prof. Smith.

To the writer it seems rather questionable whether the relation ought to be representable by a mathematical curve of any type without modification on some individual nights. There are so many conflicting forces at work on a typical night preceding a frost and the changes in some of these forces are so rapid at times, it seems possible the combined influences of all of them might not be shown best by this method alone.

CONCLUSION.

Fairly accurate minimum temperature forecasts can be made for the key stations at Medford and Pomona through the use of the hygrometric formula alone when weather conditions in the valleys are not affected by outside influences during the night. Sudden light winds which raise the temperature at night over very small areas within the valleys are difficult to forecast, but as they always cause errors on the side of safety and often affect the minimum at only a few stations in the valley they are not of very great importance.

Negative departures from the indicated minimum can practically always be forecast by noting changes in dew point in the early evening.

The formula in its present state is crude, and no doubt can be improved. However, the minimum temperature is often dependent on influences that can not be exactly represented in a simple equation, and it is unlikely a mathematical formula can ever be evolved that will be successful in every case.

The accuracy of the results obtained with the present formula is sufficient to make desirable the most exhaustive study of the whole matter, with a view to discovering methods whereby the amount of the departure of the minimum from the "normal" may be easily and successfully forecast in the early evening.

A STATISTICAL METHOD FOR PREDICTING MINIMUM TEMPERATURES.

By Henry F. Alciatore, Meteorologist.

[Dated: Weather Bureau, San Diego, Calif.; Nov. 9, 1918.]

It is the aim of this paper to present a summary of 10 unpublished reports on old and new methods for predicting minimum temperatures, prepared by the writer since his assignment to the San Diego station in April, 1917.

The San Diego fruit-frost district lies wholly within the citrus belt of San Diego County, Calif., and includes the regular Weather Bureau station at San Diego, the special meteorological stations at Escondido, El Cajon, and Bonita, and the cooperative station at Camp Kearny, Calif. Standard maximum and minimum thermometers and thermographs are in use at all stations except Camp Kearny, where the equipment does not include a thermograph. The staple products of the district are lemons, oranges, olives, grapes, and beans. The details of topography, geographical location, etc., of the stations named are given in the table below:

Table 1.—*Location of fruit-frost stations.*

	Altitude.	Distance from San Diego.	Distance from ocean.	Elevation of thermometers above ground.
	Feet.	*Miles.*	*Miles.*	*Feet.*
San Diego, Calif.	*26		4	62
Bonita, Calif.	110	8 S.E	6	4
Camp Kearny, Calif.	400	11 N.	6	4
El Cajon, Calif.	482	12 E.	16	4
Escondido, Calif.	657	28 N.	14	4

* Street level at U. S. post-office and customhouse building.

The first of the old methods to be tried was that known as the "Method of Least Squares," which had been successfully used by Prof. J. Warren Smith in his frost-protection work in Ohio. (See Monthly Weather Review, October, 1916.) The relation between two independent variables, i. e., the 5 p. m. dew point and relative humidity, and the minimum temperature of the following morning, is the basis of the method, or, as Prof. Smith has aptly stated it: "The amount of moisture in the atmosphere is a measure of the variation of the minimum temperature from the evening dew point." (See Monthly Weather Review, August, 1917.)

The records used were those of the San Diego station for five Decembers (1913–1917), which were tabulated in the same manner as were those used by Prof. Smith for Germantown, Ohio. The formula was the familiar hygrometric one, $y=a+bR$. Our table included dew point, relative humidity, and minimum temperature data for 60 December days, and, using Prof. Smith's symbols, the summations were:

n	ΣR	ΣY	ΣR^2	ΣRY
60	3687	−76	245521	−3580

Constants a and b of the hygrometric formula were: $a=28.30$; $b=-0.44$. The results obtained for December were good, but later tests (for other months) proved unsatisfactory.

Our second study was for the purpose of testing the "Median Temperature Method." (See Monthly Weather Review, October, 1914.) Complete records were available for San Diego, and more or less broken ones for the substations, for four Februarys, 1914–1917.

Results from this method were unsatisfactory. This was due in a large measure to the fact that in this part of the country the times of occurrence of the median temperatures vary within very large limits, much larger than in the Eastern States. For example: The earliest time at San Diego was 4:30 p. m., and the latest, 9:35 p. m., and average time, 7:03 p. m. In this test, only 17 out of 26 forecasts were close to the observed minimum temperatures at San Diego, and the forecasts for the rural stations were no better. We studied the pressure and wind data in the hope of finding an explanation for the large variations of the predicted from the observed values. The prevailing winds (midnight to 7 a. m.) on 18 mornings for which good forecasts were made were as follows:

From E.-NE.	14 times.
N	2
NW	1
SE	1

It would seem, then, that normal winds, i. e., E.-NE., are the most favorable for frost formation. As to pressure factor, no clearly defined relation was observed between the pressure at 5 p. m. and the minimum of the following morning. The coldest morning (minimum, 38°) did *not* follow the evening with the highest pressure. The warmest morning (minimum, 51°) followed a reduced evening pressure of 30.11 inches. Finally, evening pressures of 29.96 and 30.23 inches, respectively, were followed by identical temperatures the following morning, namely, 46°. These facts are contrary to theory.

FIRST STATISTICAL METHOD.

The statistical method that we proposed last April for making 12-hour predictions of minimum temperature was the result of experiments made with hundreds of dew-point humidity combinations in the course of which we had been struck by the frequent recurrence, on clear mornings, of the same or sensibly the same minimum temperatures with a given D. P.-R. H. combination. This recurrence phenomenon forms the basis of the new method.

The data used in this study were of the same kind as before, i. e., the 5 p. m. dew point and humidity and the minimum temperature of the following morning, all of which were extracted from the "Original Record of Observations" (Form 1001-Metl.) of the San Diego Weather Bureau office. It occurred to us to group

the data for the month of March for a period of five years (1913–1917), as shown in part in Table 2, and to determine the probable minimum temperature from the group means, as in the following example:

TABLE 2.—*Dew point and relative humidity at 5 p. m., Pacific time, and minimum temperature of the following morning, for the month of March for five years to 1917, at San Diego, Calif.*

(D. is the dew point; H., relative humidity; M., minimum temperature.)

Relative humidity.	D.	H.	M.	Relative humidity.	D.	H.	M.	Relative humidity.	D.	H.	M.
Per cent.				*Per cent.*				*Per cent.*			
10–19......	26	13	55	30–39......	31	30	48	40–49......	36	40	44
					32	34	46		38	43	44
20–29......	28	24	49		34	39	44		37	46	43
				Means.....	32	34	46	Means.....	37	43	44
	31	20	51								
	32	21	54		38	36	48		42	46	50
	33	22	52		35	36	49				
Means......	32	21	52		37	36	48		48	47	53
					36	35	46		47	48	53
	36	24	54	Means.....	36	36	48		45	47	46
	39	29	54					Means.....	47	47	51
	38	24	55		44	35	48				
Means......	38	26	54						52	48	54
					50	38	60		52	47	56
	44	29	57		50	39	58		51	46	58
				Means.....	50	38	59	Means.....	52	47	56

March 1, 1918. Dew point, 35; relative humidity, 30. By Table 2, the nearest class means are 36–36, with a minimum temperature of 48°, the last-named value being the probable temperature for the next morning. The observed minimum was 52°, that is, 4° higher than the predicted temperature. Twelve trial forecasts were made by this method. The data used and results obtained are set forth in Table 3. It will be noted that the greatest departure from the prediction was 4°, and that in five cases the predicted and the observed values were identical.

TABLE 3.—*Showing results of tests of the statistical method for March, 1918, at San Diego, Calif.*

(D. is the 5 p. m. dew point; H., the 5 p. m. relative humidity; M., the observed minimum temperature of the following morning; F., the predicted minimum temperature; and V., the variation of the predicted from the observed minimum temperature.)

SAN DIEGO, CALIF.

Day.	D.	H.	M.	F.	V.	Day.	D.	H.	M.	F.	V.
1918.						1918.					
Mar. 1........	35	30	52	48	4	Mar. 15........	52	58	54	55	1
2........	41	40	50	50	0	20........	49	70	51	50	1
8........	41	54	44	46	2	27........	52	75	51	50	1
12........	56	88	48	52	4	28........	53	69	50	50	0
13........	44	56	47	44	3	29........	55	70	54	54	0
14........	50	60	49	49	0	30........	52	52	55	55	0

The discovery made at this time, that the evening dew-point humidity combinations might also be used for predicting the character of the weather of the following morning about sunrise, was a curious feature of this investigation. To illustrate: Of the 40 evenings in the five-year period named, on which the relative humidity was 70 per cent or over, with dew points of 49° to 59°, 85 per cent were followed the next morning by cloudy or partly cloudy weather, and the other 15 per cent by clear skies.

SECOND STATISTICAL METHOD.

A desire to improve the method described above led us to undertake another study last August. The fundamental idea of this, our latest effort, which might be called "A Statistical Method of Progressive Means for Predicting Minimum Temperatures," was suggested by Dr. Henry Ludwell Moore's valuable work on "Forecasting the Yield and Price of Cotton," a recent addition to our station library.

The records for 17 Decembers (1900–1916) were tabulated as shown partially in Table 4, in which the humidity values are arranged in the order of their magnitudes and the resultant progressive means of dew point, relative humidity, and minimum temperatures entered in parallel columns. A few of the combinations (such as 35–32–51) were omitted from the progressive means because it was obvious that the temperature values were not related at all with the humidity or dew point. The combinations thus omitted from Table 4 are indicated by a star.

TABLE 4.—*Showing evening dew points and relative humidities (5 p. m., Pacific time) and minimum temperatures the following morning for 17 Decembers to 1916, inclusive, with computed progressive means, for San Diego, Calif.*

(The minimum temperatures are those observed on clear mornings only. D. is the dew point; H., relative humidity; and M., minimum temperature.)

Observed.			Progressive means.		
D.	H.	M.	D.	H.	M.
−14	3	49	−14	3	49
− 4	5	45	− 9	4	47
− 2	5	44	− 7	5	46
4	9	45	− 4	6	46
17	13	40	0	7	46
17	19	38	3	9	45
21	20	43	21	20	43
22	20	53	....	....	(*)
23	21	43	22	20	43
24	29	48	....	....	(*)
26	20	52	26	20	52
26	20	49	26	20	50
26	33	37	26	24	46
27	20	54	27	20	54
28	21	51	28	20	52
29	23	53	28	21	53
29	30	47	28	24	51
29	31	49	28	25	51
29	32	45	28	26	50
30	20	53	30	20	53
30	32	42	30	26	48
30	38	38	30	30	44
30	43	36	30	33	42
31	21	57	31	21	57
31	26	55	31	24	56
31	44	39	31	30	50
32	22	58	32	22	58
32	24	55	32	23	56
32	29	51	32	25	55
32	29	47	32	26	53
32	31	49	32	27	52
32	42	37	32	30	50
32	44	38	32	32	48
32	56	35	32	35	46

*Indicates a dew-point humidity combination whose corresponding minimum temperature departs materially from that required by the hygrometric formula. Omitted from the progressive means.

The progressive means were obtained as illustrated in detail in Table 5, which shows that with a dew point of 38°, an increase of 17 per cent in humidity (30–47), there

is a drop of 9° (53–44) in the minimum temperature. The predicted minimum will be 9/17° lower than the initial progressive mean of temperature in the table (53) for each increase of 1 per cent in the humidity. Table 4 shows that this ratio varies within large limits with different dew points, for at dew point 30 it is 0.85°, while at dew point 56 it is only 0.22°.

TABLE 5.—*Showing method for obtaining progressive means of relative humidities and minimum temperatures at San Diego, Calif., with a dew point of 38° and differing humidities.*

(See 13th group of Table 4.)

SAN DIEGO, CALIF.

Observed values.						Progressive means.		
D.	Sum.	H.	Sum.	M.	Sum.	D.	H.	M.
38	......	30	......	53	......	38	30	53
38	76	40	70	48	101	38	35	50
38	114	46	116	43	144	38	39	48
38	152	47	163	42	186	38	41	46
38	190	51	214	38	224	38	43	45
38	228	54	268	42	266	38	45	44
38	266	58	326	39	305	38	47	44

Following is the formula for predicting temperatures by the second statistical method:

$$F = M - \left(\frac{M - M_1}{H - H_1}\right)(H_2 - H_1)$$

where—

F, is the predicted minimum temperature.

M, highest temperature in the table for the 5 p. m. dew point observed on forecast day.

M_1, the lowest table temperature.

H, the highest tabular humidity.

H_1, the lowest tabular humidity.

H_2, the humidity observed at 5 p. m. on forecast day.

Example.—Given a dew point of 32°, and a relative humidity of 28 per cent, to find the probable minimum temperature of the following morning. Substituting the proper values, from Table 4, we have:

$$F = 58 - \left(\frac{58-46}{35-22}\right)(28-22)$$

Therefore,

$$F = 58 - 5.5 = 52.5. \quad \text{Ans.}$$

For the purpose of testing out the second statistical method we picked out the evenings in December, 1917 (a month whose data were not used in computing progressive means), at San Diego next preceding mornings on which freezing or lower temperatures had actually been recorded, *not* at San Diego, but at one or more rural stations in the district, regardless of sky conditions at the base station. The data used and results obtained are given in detail in Table 6, the most striking feature of which is the fact that 18 out of 19 predictions showed a variation from the observed of less than 4°. The forecast of December 10, for a minimum temperature of 54°, was the worst of the lot, the variation being 8°. This failure may be ascribed in part to the fact that we had but two combinations (Table 4) to work with, both of which indicated unusually high minimum temperatures relatively to their respective dew points and humidities. One of these, the first (58–88–51), is known to have occurred on a day (Dec. 7, 1915) when, owing to the pressure distribution over the district, no frost warning would have been issued. This circumstance points to a possible improvement in the method, namely, that in tabulating data of this kind in future no combinations should be used in computing means unless clearly associated with anticyclonic systems of pressure distribution. Nevertheless, the results of the December, 1917, test are all the more remarkable in that neither wind, cloudiness, nor pressure was taken into account in making the forecasts.

TABLE 6.—*Showing evening dew points and relative humidities (5 p. m., Pacific time) at San Diego, Calif., for 19 days in December, 1917, next preceding mornings on which freezing or lower temperatures were recorded at one or more rural stations, and the observed and predicted temperatures, with the variations of the predicted from the observed minimum temperatures, by the method of progressive means.*

SAN DIEGO, CALIF.

Day.	D.	H.	M.	F.	V.	Day.	D.	H.	M.	F.	V.
1917.						1917.					
Dec. 3........	54	85	46	46	0	Dec. 14........	55	88	46	48	2
4........	47	59	50	50	0	15........	54	83	45	48	3
6........	59	90	49	52	3	16........	54	88	47	45	−2
7........	39	36	48	51	3	17........	52	78	50	47	−3
8........	31	27	52	52	0	19........	56	74	53	53	0
9........	32	28	50	52	2	20........	44	49	52	50	−2
10........	57	86	46	54	8	21........	55	96	45	46	1
11........	50	72	44	47	3	22........	54	86	49	46	−3
12........	53	83	45	48	3	24........	50	74	46	47	1
13........	56	88	46	49	3						

NOTE.—D. is the dew point; H., the relative humidity; M., the observed minimum; and F., the predicted minimum temperature; V., the variation of the predicted from the observed minimum temperature.

By the same method we made a test of the November, 1917, data, and obtained even better results. (See Table 7.) The most interesting things about this last test are: (1) That all of the 15 forecasts made were satisfactory, since the greatest variation was only 3°; (2) that the forecasts were based on the *December*, not the November, dew-point humidity combinations. In other words, we used the combinations in Table 4 for both tests. We did this at the suggestion of First Assistant Dean Blake, whose help in checking my computations and sympathetic cooperation are gratefully acknowledged here. Mr. Blake's idea was that, perhaps, one set of combinations might be made to answer for predicting minimum temperatures for all the cold months of the year. At this writing, we are in doubt as to whether to attribute the good results of the November-December tests to the correctness of the method or to the well-known equability of temperature that characterizes the climate of San Diego at all seasons. A test of this method at some place where the winter temperatures are very variable would settle the question and would prove interesting to forecasters.

TABLE 7.—*Showing evening dew points and relative humidities (5 p. m., Pacific time) at San Diego, Calif., for 15 days in November, 1917, next preceding mornings on which freezing or lower temperatures were recorded at one or more rural stations, and the observed and predicted temperatures, with the variations of the predicted minimum from the observed minimum temperatures, by the method of progressive means.*

SAN DIEGO, CALIF.

Day.	D.	H.	M.	F.	V.	Day.	D.	H.	M.	F.	V.
1917.						1917.					
Nov. 7	47	60	48	49	1	Nov. 19	44	34	55	58	3
8	52	73	49	48	−1	20	31	20	55	57	2
13	55	83	53	51	−2	22	45	45	54	53	1
14	53	75	48	50	2	25	52	76	49	47	−2
15	56	82	49	49	0	26	55	83	49	41	2
16	58	86	52	51	−1	28	56	87	46	48	2
17	46	41	53	54	1	29	57	88	47	50	3
18	50	50	56	58	2						

NOTE.—D. is the dew point; H., relative humidity; M., the observed minimum; and F., the predicted minimum temperature; V., the variation of the predicted from the observed minimum temperature.

Dr. G. F. McEwen (hydrographer at the Scripps Biological Institute, La Jolla, Calif., near San Diego), who has been good enough to review our second statistical method, has pointed out that it is open to two objections, namely: (1) That the values of *M* in our formula may be too high or too low in some cases, relatively to the corresponding dew point and humidity, since they are not progressive means but individual values; (2) that should we meet with an unprecedented D. P.–R. H. combination in our forecast work, we would have to use the nearest combination found in the table of means, a combination which itself might be unreliable.

The great interest taken in our statistical work by Dr. McEwen moved us to invite him to undertake a mathematical study of our data for December. An account of Dr. McEwen's investigation appears in a companion paper. We believe that his prediction chart for forecasting minimum temperatures at San Diego will prove to be a distinct advance on former methods and very valuable.

TABLE 7a.—*Comparative statement of minimum temperature predictions made by the statistical and the successive approximation methods, for November and December, 1917, at San Diego.*

[A., statistical method; B., successive approximation method.]

SAN DIEGO, CALIF.

Day.	A.		B.		Day.	A.		B.	
	F.	V.	F.	V.		F.	V.	F.	V.
1917.					1917.				
Nov. 7	49	1	48	0	Dec. 3	46	0	48	2
8	48	−1	48	−1	4	50	0	49	−1
13	51	−2	49	−4	6	52	3	52	3
14	50	2	49	1	7	51	3	49	1
15	49	0	50	1	8	52	0	49	−3
16	51	−1	52	0	9	52	2	49	−1
17	54	1	54	1	10	54	8	51	5
18	58	2	54	−2	11	47	3	47	3
19	58	3	55	0	12	48	3	48	3
20	57	2	52	−3	13	49	3	49	3
22	53	1	51	−3	14	48	2	48	2
25	47	−2	48	−1	15	48	3	49	4
26	41	2	49	0	16	45	−2	47	0
28	48	2	49	3	17	47	−3	48	−2
29	50	3	50	3	19	53	0	52	−1
Sums	......	25	......	23	20	50	−2	49	−3
					21	46	1	46	1
					22	46	−3	48	−1
					24	47	1	46	0
					Sums	......	42	......	39

In Table 7a we give the minimum temperatures predicted by the statistical and the "successive approximation" methods, with their variations from the observed values, for November and December, 1917. The sums of the variations show that the McEwen method gave somewhat closer forecasts. The data upon which the McEwen predictions were based were computed by the method of successive approximations to the means by Dr. McEwen. How to use the data is explained in his paper.

So far we have confined our remarks to a discussion of methods for predicting temperatures at the base station, i. e., San Diego. Now we shall consider the second and, by far, the more difficult phase of our problem, namely, how to apply the predicted temperatures for the base station to the determining of probable minimum temperatures at the rural stations. At the beginning of our investigation it seemed to us that on clear mornings with anticyclonic pressure conditions over the district the relation between the minimum temperatures at the rural stations and those at the base station would be fairly constant for any winter month from year to year. Later on we found that the mean variation between the two sets of temperature values fluctuates within very wide limits. As this is a very important matter we have tabulated (Table 8) the actual temperature variations at the rural stations for two months of different names for several years, the better to drive home the discouraging circumstance, from the forecasting viewpoint, that one year, for instance, the variation between Escondido and San Diego was only 9.8° and another year it was more than 15°, i. e., in December, 1914, and December, 1916, respectively. It is obvious that these two months must have differed materially in other meteorological factors besides dew points and humidities. The records of the other rural stations show that similar departures may be expected in different years at those places also. It is also evident that such wide divergences can not be explained by topographical considerations. In one test made by applying the correction factors taken from Table 9 the results (see Table 10) made one thing perfectly clear, i. e., that one season we might make excellent, and the next season poor, forecasts, quite regardless of the character of the predictions that might be made for the base station. It follows, then, that while we may claim to have made some progress toward solving our problem in so far as base-station predictions are concerned, yet there remains to be solved the problem of predicting the rural-station temperatures, either by the method already described, or by another and more reliable forecasting scheme. However, we are planning another investigation, to include a study of types of wind and pressure distributions, and a regrouping of the dew point and humidity values with reference to these two factors which, it is hoped, will help us solve this difficult problem.

TABLE 8.—*Showing average minimum temperatures at four places in the San Diego fruit-frost district, and the mean, greatest, and least variations of the rural-station temperatures from those of the base station. (The values are for mornings on which the sky at San Diego was less than four-tenths overcast.)*

Year and month.	San Diego.	Escondido.	El Cajon.	Bonita.
November:				
1913	53.5	41.2	44.6	*48.6
1914	56.4	43.2	45.1	*49.2
1915	48.6	34.8	36.5	40.0
1916	46.6	33.0	34.4	37.3
Means	51.3	38.0	40.2	43.2
Average variation		−13.3	−11.1	−7.5
Greatest variation		−14.0	−12.3	−9.3
Least variation		−12.3	− 8.9	−4.9
December:				
1913	46.9	33.2	35.6	*38.4
1914	45.5	35.7	38.2	*41.3
1915	46.5	33.5	35.4	*38.2
1916	42.1	26.9	30.2	32.6
Means	45.2	32.3	34.8	37.6
Average variation		−12.9	−10.4	−7.6
Greatest variation		−15.2	−11.9	−9.5
Least variation		− 9.8	− 7.3	−4.2

*Interpolated values.

TABLE 9.—*Showing dew points and relative humidities at 5 p. m., Pacific time; observed minimum temperatures the following morning; predicted minimum temperatures and their variations from the observed values at San Diego; and the predicted and observed minimum temperatures (with their respective variations) for Escondido, El Cajon, and Bonita, for November, 1917.*

(D. is the dew point; H., relative humidity; M., observed minimum temperature; F., predicted minimum temperature; V., variation of the predicted from the observed minimum temperature.)

Date.	San Diego (base station).					Escondido (correction −13°).			El Cajon (correction −11°).			Bonita (correction −8°).		
	D.	H.	M.	F.	V.	M.	F.	V.	M.	F.	V.	M.	F.	V.
1917.														
Nov. 7	47	60	48	40	1	34	36	2	40	38	−2	41	41	0
8	52	73	49	48	−1	35	35	0	40	37	−3	41	40	−1
13	55	83	53	52	−1	39	39	0	47	41	−6	47	44	−3
14	53	75	48	48	1	32	36	4	38	38	0	41	41	0
15	56	82	49	51	2	31	38	7	35	40	5	39	43	4
16	58	86	52	50	−2	33	37	4	36	39	3	40	42	2
17	46	41	53	54	1	55	41	−14	38	43	5	45	46	1
18	50	50	56	56	0	41	43	2	43	45	2	47	48	1
19	44	34	55	58	3	44	45	1	41	47	6	43	50	7
20	31	20	55	52	−3	38	39	1	40	41	1	44	44	0
22	45	45	54	53	−1	40	40	0	41	42	1	45	45	0
25	52	76	49	47	−2	32	34	2	36	36	0	40	39	−1
26	55	83	49	52	3	31	39	8	36	41	5	38	44	6
28	56	87	46	47	1	29	34	5	34	36	2	36	39	3
29	57	88	47	53	6	31	40	9	34	42	8	36	45	11

THE MINIMUM TEMPERATURE, A FUNCTION OF THE DEW POINT AND HUMIDITY, AT 5 P. M. OF THE PRECEDING DAY; METHOD OF DETERMINING THIS FUNCTION BY SUCCESSIVE APPROXIMATIONS TO GROUP AVERAGES.

By GEORGE F. McEWEN, Hydrographer of the Scripps Institution for Biological Research of the University of California.

[Dated: La Jolla, Calif., Nov. 12, 1918.]

INTRODUCTION.

From studying the San Diego meteorological records the meterologist, Mr. Alciatore, concluded that there was a close relation between the minimum temperature for any day and the dew point and humidity of the preceeding afternoon. Prior to this discovery, considerable use had been made of the observed relation of the minimum temperature to humidity in predicting minimum temperatures. But the need of taking into account the dew point became more and more apparent, and various methods of using both the humidity and dew point in making these predictions have been tried. Mr. Alciatore, the San Diego meteorologist, has applied the method of "progressive means" to local data, and the increased accuracy of prediction based on his method demonstrated the importance of using the dew point as well as the humidity, at least in this region. His results also confirm the conclusion reached by Prof. J. Warren Smith, that the relation of the temperature to both the dew point and humidity is not linear.

However, certain defects of Mr. Alciatore's preliminary method were recognized, and he felt the need of a more elaborate system of determining the relation. One of the results of the writer's cooperation at the Scripps Institution in researches on the quantitative relation between marine organisms and their environment is a successive approximation method of determining the functional relation between one variable and each of a number of correlated variables, and an examination of Mr. Alciatore's data showed that the same method would serve to obtain the relation he desired.

In order to aid others in solving similar statistical problems, Mr. Alciatore requested me to prepare the following brief description of the method of successive approximation to group means and its application to the meteorological problems of predicting minimum temperatures.

GENERAL PRINCIPLES OF THE METHOD OF SUCCESSIVE APPROXIMATIONS TO GROUP MEANS.

As would be expected in such a problem, the two independent variables (dew point $=D$ and humidity $=H$) selected do not suffice to determine completely the minimum temperature, M. For a given pair of values of H and D the observed values of M fluctuate about some mean value on account of other factors, which at this preliminary stage of the work are neglected. Consequently, in determining the functional relation we must work with *averages* in order to eliminate as far as possible the effect of the *accidental variation* due to the neglected factors.

Accordingly, arrange the values of one independent variable, say D, in their order of magnitude along with the corresponding observed values of M, and an index number, to be used in identifying any entry with the original record. Such a table indicates the relation of M to D, but each value of M is subject to an accidental error and to a variation with respect to H as well. And it is necessary to eliminate both of these effects as far as possible. To eliminate the accidental error, divide the series into groups having successively n_1, n_2, n_3, etc., entries, and take the average value of the independent variable and the corresponding dependent variable of each group.

Deciding upon the number of entries n in a group is a matter of judgment and depends upon the magnitude of the accidental error, the number of observations available, and the range of values of the independent variables. In this series of averages the number of entries per group will be assumed large enough to reduce sufficiently the effect of the accidental errors. It remains to eliminate the effect of the variations in the second independent variable H. If the average of the values of H were the same for each of the D groups, then the variations in H would evidently not affect the averages of M. In that case H could be regarded as constant, and the above series would define the approximate functional relations of M to D. If, as is the case in this problem, there is a correlation of the values of H and D, that is, if in the successive groups with respect to D the values of H either increase or decrease, on the average, the differences in the successive values of the M averages depend upon both H and D, and it is necessary to apply corrections which will reduce the M averages to what they would have been if H had not varied or was not correlated with D.

Next, tabulate the values of M with respect to H, in which the values of H are arranged in their order of magnitude. Divide these values into groups and take averages as in the first or D series. This series of averages may indicate an approximation to the relation of M to H, but corrections must be applied to eliminate the effect of the correlation of H and D. An approximate correction to the first or M D series can be made by regarding the second or M H one as accurate. Then, by means of the corrected M D series, apply corrections to the M H series and so on until the successive approximations to the averages converge to definite limiting values. It can be shown that the relation defined by these limiting values of the averages in each series is not disturbed by the correlation of the independent variables H and D. That is, one series defines the relation of M to D, and the independent variables correlated with D, but not with H,

and, similarly, the other series defines the relation of M to H and the independent variables correlated with H but not with D.

NUMERICAL APPLICATION OF THE METHOD, ILLUSTRATED BY DETERMINING THE RELATION OF THE MINIMUM TEMPERATURES TO THE DEW POINT AND HUMIDITY AT SAN DIEGO.

The San Diego data (see Table IV of Mr. Alciatore's paper) for clear days (cloudiness 0 to 0.3 at 4:45 a. m.) in the December months for 17 years up to 1916 contained 235 entries. These entries were first arranged in the order of magnitude of the dew point, D, and second in the order of magnitude of the humidity, H. In each series the entries were separated into five groups, there being 50 in the first two and last two and 35 in the middle group of each series. For convenience, the five groups with respect to dew point were denoted by the letters A, B, C, D, and E, respectively, and the five groups with respect to humidity by F, G, H, I, and J. The preliminary results are given in Tables 1 and 2.

TABLE 1.—*Minimum temperature and dew point.*

Groups.	*A.*	*B.*	*C.*	*D.*	*E.*
Number per group	50	50	35	50	50
Sums of values of M	2,302	2,290	1,656	2,341	2,446
Average value of M	46.04	45.80	47.31	46.82	48.92
Range of values of M	35-58	38-60	41-56	40-55	41-59
Sums of values of the dew point	1,403	2,014	1,656	2,460	2,694
Average values of the dew point	28.1	40.3	45.6	49.2	53.9
Range of values of dew point	14-36	37-44	44-47	47-51	51-60
Subgroups.	Number of entries common to each group and subgroup.				
F	37	13	0	0	0
G	13	23	12	2	0
H	0	11	13	9	2
I	0	2	9	28	11
J	0	1	1	11	37

TABLE 2.—*Minimum temperature and humidty.*

Groups.	*F.*	*G.*	*H.*	*I.*	*J.*
Number per group	50	50	35	50	50
Sums of values of M	2,476	2,268	1,622	2,325	2,344
Average values of M	49.52	45.36	46.34	46.50	46.88
Range of values of M	38-60	35-59	39-59	38-55	38-55
Sums of values of the humidity	1,369	2,453	2,137	3,578	4,210
Average values of the humidity	27.4	49.1	61.1	71.5	84.2
Range of values of humidity	3-41	41-56	56-66	66-77	77-99
Subgroups.	Number of entries common to each group and subgroup.				
A	37	13	0	0	0
B	13	23	11	2	1
C	0	12	28	9	1
D	0	2	9	28	11
E	0	0	2	11	37

It remains to reduce the temperature averages of the dew-point groups (Table 1) to what they would have been if the humidity had a constant value, say, 61.1, of the middle group in Table 2, and similarly to reduce the temperature averages of the humidity groups (Table 2) to what they would have been if the dew point had a constant value, say, 45.6, of the middle group in Table 1. To do this, classify the entries in each dew-point group with respect to the humidity groups. For example, in group A the original tabulation (Table 4 of Mr. Alciatore's paper) shows that 37 entries are also in group F, 13 are in group G, and none are in the H, I, and J groups. Accordingly, the numbers 37, 13, 0, 0, 0 are entered in the last five lines of column A, Table 1. In the same way, by counting the number of subgroups F, G, H, I, and J represented in each of the remaining groups B to E, the remaining entries in the last five lines are found. And in Table 2, A to E, are subgroups whose distribution in the F to J groups is shown by the numbers in the last five lines. If there were no correlation between the independent variables, humidity and dew point, the number of subgroups would be equally distributed. In this case, as we pass to higher humidity groups—that is, to the right, from F to J, in Table 2, there is an increasing proportion of higher dew-point subgroups. That is, as the humidity increases the dew point increases, and the effect of this correlation must be eliminated. This can be done as follows:

In group A, Table 1, 37 entries are also in the subgroup F, and to each of these we must add the difference $(46.34-49.52=-3.18)$ from Table 2 to correct it to the constant value 61.1 of the humidity in the middle or H group. Similarly, to each of the 13 entries of A that are also in the subgroup G we must add $(46.34-45.36=0.98)$ from Table 2. The correction to the sum 2302 in the A group is therefore $\{37\times(46.34-49.52)+13\times(46.34-45.36)\}=-104.92$, and the correction to the average 46.04 is $-104.92\div 50=-2.10$. In the same way the corrections to the remaining averages in groups B to E can be found, and from these corrected averages the averages F to J can be corrected. Then the A to E series can be corrected again, using these new averages in the F and J series, and so on. The limiting values of these successive approximations will be the corrected averages desired.

The process can be systematically carried out, as shown by Tables 3 and 4. The small letters f, g, i, and j (Table 3) denote the result of subtracting the average temperature of groups F, G, I, amd J, respectively, from the average for the middle or H group. Similarly, the letters a, b, d, e, (Table 4) denote the differences between the temperature averages of the middle or C group of the dew-point series and each of the A to E values (Table 3).

The numbers in the sub-group lists of Tables 3and 4 are taken directly from Tables 1 and 2, respectively. And the differences are entered under f, g, i, and j, and a, b, d, e, respectively, in the order found. In this case from Table 2 the values $f=46.34-49.52=-3.18$, $g=(46.34-45.36)=0.98$, etc., are entered in the first line of Table 3. Multiplying these values by the numbers in line A, and dividing by 50, the number of entries in the A group gives the correction, A' to the A average. In the same way the

corrections to the remaining averages B to E can be found. These corrections are entered in the columns A' to E' on the same lines as the differences on which they depend. And the corrected averages are entered on the same line in columns A to E. The differences $a=(47.59-43.94)=+3.65$, etc., are then entered in columns a, b, d, and e of Table 4, and the corrections and corrected averages in columns F' to J' and F to J, respectively.

TABLE 3.—*Form for entering the computation of the averages A to E.*

f	g	i	j	A'	B'	C'	D'	E'	A	B	C	D	E	No. of the approximation.
									46.04	45.80	47.31	46.82	48.92	1
−3.18	0.98	−0.16	−0.54	−2.10	−0.39	0.28	−0.17	−0.43	43.94	45.41	47.59	46.65	48.49	2
−5.57	−.13	.30	.76	−4.16	−1.48	.05	.33	.63	41.88	44.32	47.36	47.15	49.55	3
−7.15	−.97	.96	1.85	−5.54	−2.23	−.03	.91	1.58	40.49	43.57	47.28	47.73	50.50	4
−8.30	−1.60	1.52	2.73											
−9.17	−2.00	1.95	3.16											
f'	g'	i'	j'	A''	B''	C''	D''	E''						No. of the approximation.
−2.39	−1.11	0.46	1.30	−2.06	−1.09	−0.23	0.50	1.06	41.88	44.32	47.36	47.15	49.55	3
−1.58	−.84	.06	1.00	−1.39	−0.75	−.09	.58	.95	40.49	43.57	47.27	47.73	50.50	4
−1.15	−.63	.56	.88	−1.01	−.55	−.05	.48	.77	39.48	43.02	47.22	48.21	51.27	5
−.87	−.49	.43	.43	−.77	−.43	−.05	.32	.41	38.71	42.59	47.17	48.53	51.68	6
f''	g''	i''	j''	A'''	B'''	C'''	D'''	E'''	A''	B''	C''	D''	E''	No. of the approximation.
0.43	0.21	−0.10	−0.21	0.37	0.20	0.04	−0.09	−0.18	−1.02	−0.55	−0.05	0.49	0.77	5
.28	.14	−.13	−.45	.24	.12	.00	−.17	−.36	−.77	−.43	−.05	.31	.41	6

NUMBER OF SUBGROUPS.

A	B	C	D	E	
37	13	0	0	0	f
13	23	12	2	0	g
0	2	9	28	11	i
0	1	1	11	37	j

FINAL VALUES OF THE AVERAGES OBTAINED AT THE FIFTEENTH APPROXIMATION.

A	B	C	D	E
36.5	41.4	47.1	49.5	53.4

A continuation of this process will lead to limiting values differing from those found in the next approximation by less than the assumed limit of error, thus completing the computation. In general, it is well to carry the computation one place farther than is desired in the final result. For example, in this problem the computation is carried to hundredths of a degree, but the final result is accurate to tenths of a degree. Also, the computation can be checked for each approximation by computing corrections to the averages last found, using differences between successive values of each of the quantities a to b and f to j. This is illustrated by the columns a', b', d', e', f', g', i', j', where a' equals the nth value of a minus the (n–1)th value of a, etc. The corrections to the (n–1)th approximation to A, B, etc. (Table 3), are entered in columns A'', B'', etc., and the nth approximation to the averages in columns A, B, etc. These averages should agree with the corresponding ones above.

In the same way the corrections F'', G'', etc., and the nth approximations to the averages F, G, etc., of the Table 4 are found.

After the first four approximations, the computation of the corrections A'', B'', etc., can be checked by using the differences f'' equals nth value of f' minus the (n–1)th value of f', etc., to obtain the corrections A''', B''', etc., to the value of A'', B'', etc., last found. The same multipliers (entries in the last five lines of the table) are used for f, f', f'', and g, g', g'', etc. And it is unnecessary from then on to compute the corrections to the original averages. Tables 3 and 4 show the work required for the first six approximations only. Owing to the high correlation between the independent variables, 15 approximations were required to obtain the desired accuracy.

TABLE 4.—*Form for entering the computation of the averages F. to G.*

a	*b*	*d*	*e*	*F'*	*G'*	*H'*	*I'*	*J'*	*F*	*G*	*H*	*I*	*J*	No. of the approximation.
									49.52	45.36	46.34	46.50	46.88	1
3.65	2.18	0.94	−0.90	3.27	1.99	0.88	0.42	−0.42	52.79	47.35	47.22	46.92	46.46	2
5.48	3.04	.21	−2.19	4.85	2.83	.88	− .24	−1.51	54.37	48.19	47.22	46.26	45.37	3
6.79	3.71	− .45	−3.22	5.99	3.45	.87	− .81	−2.41	55.51	48.81	47.21	45.69	44.48	4
7.74	4.20	− .99	−4.05											
8.46	4.56	1.36	−4.51											
a'	*b'*	*d'*	*e'*	*F''*	*G''*	*H''*	*I''*	*J''*						
1.83	0.86	−0.73	−1.29	1.58	0.84	0.01	−0.66	−1.10	54.37	48.19	47.23	46.26	45.36	3
1.31	.67	− .66	−1.03	1.14	.62	− .02	− .57	− .89	55.51	48.81	47.20	45.69	44.48	4
.95	.49	− .54	− .83	.83	.45	− .03	− .47	− .72	56.34	49.26	47.17	45.22	44.01	5
.72	.36	− .37	− .46	.66	.34	− .01	− .29	− .41	56.97	49.00	47.16	44.93	43.60	6
a''	*b''*	*d''*	*e''*	*F'''*	*G'''*	*H'''*	*I'''*	*J'''*	*F''*	*G''*	*H''*	*I''*	*J''*	
−0.52	−0.19	0.07	0.26	−0.43	−0.22	−0.03	0.09	0.21	1.15	0.62	−0.02	−0.57	−0.89	4
− .36	− .18	.12	.20	− .31	− .17	− .01	.10	.17	.83	.45	− .03	− .47	− .72	5

NUMBER OF SUBGROUPS.

F	*G*	*H*	*I*	*J*	
37	13	0	0	0	*a*
13	23	11	2	1	*b*
0	2	9	28	11	*c*
0	0	2	11	37	*d*

FINAL VALUES OF THE AVERAGES OBTAINED AT THE FIFTEENTH APPROXIMATION.

F	*G*	*H*	*I*	*J*
58.8	50.6	47.1	44.0	42.0

The method of successive approximation can be readily applied, whatever the number of independent variables or groups. In making the correction by using subgroups as above described, it is assumed that each observed value of M corresponds to the mean value of the independent variable in that subgroup. Actually, each value of M corresponds to some value of the independent variable within the extreme values in the group in question. The error involved in this assumption is smaller, the smaller the range of the independent variable in the subgroup, and the more uniformly the values of the independent variable are distributed about the mean of the subgroup. This error can, if desired, be approximately corrected by assuming the regression to be linear with respect to the corresponding independent variable in each group. The first approximation found by finding the regression, using the given entries, can be successively corrected by a method similar to that above described for using subgroup averages. However, this refinement at least doubles the labor and need not be used unless the data are so deficient as to necessitate a wide range in the values of the independent variable in order to obtain a sufficient number of entries per group. Moreover, in any given problem this correction can be applied to any arbitrarily selected groups and need not be applied to all.

The writer has worked out a mathematical demonstration of the general method of successive approximation,* and in order to test the method Messrs. Michael and Collins, biologists in the Scripps Institution, are applying it to biological problems. The results of these tests are very encouraging and will be published when completed.

PRACTICAL METHOD OF FORECASTING THE MINIMUM TEMPERATURE FROM ITS RELATION TO THE DEW POINT AND HUMIDITY.

The result of applying the method of successive approximation to the meteorological data is, first, a series of average minimum temperatures corresponding to a series of average values of the dew point and a constant humidity; second, a series of average minimum temperatures corresponding to a series of average values of the humidity and a constant dew point. In the problem just worked out the numerical values of the averages (see Tables 1, 2, 3, and 4) are presented in Table 5.

TABLE 5.—*The average relation of the minimum temperature to the humidity and dew point.*

Humidity		61.1			
Dew point	28.1	40.8	45.6	49.2	53.9
Minimum temperature	36.5	41.4	47.1	49.5	53.4
Dew point		45.6			
Humidity	27.4	49.1	61.1	71.5	84.2
Minimum temperature	58.8	50.6	47.1	44.0	42.0

This table presents the relations that hold, on the average, for the data used. For example, if the dew point is 45.6 and the humidity is 61.1, the minimum temperature would be expected to fluctuate about the mean value 47.1. The variation of observed values corresponding to $D = 45.6$ and $H = 61.1$ from this mean value 47.1 of the minimum temperature depends upon the importance of the neglected factors. For any other pair of values of H and D within the limits of the averages the

*McEwen, Geo. F., and Michael, Ellis L.: The functional relation of one variable to each of a number of correlated variables determined by a method of successive approximation, by Wm. E. Ritter. Proc. Amer. Acad. Arts and Sciences, vol. 55, No. 2, 1919, pp. 91-133.

mean value of the minimum temperature can be found by proportion as follows:

Let H_1 and H_2 be two successive values of the averages in the table such that H is greater than H_1 but less than H_2. Similarly, let D_1 and D_2 be successive values of the averages in the table such that D is greater than D_1 but less than D_2. Let the corresponding averages of the minimum temperature in Table 5 be M_1, M_2 (third line), M^1_1, and M^1_2 (sixth line). Then, by linear interpolation between the successive averages,

$$M = 47.1 + \left(\frac{M_2 - M_1}{H_2 - H_1}\,(H - H_1) + M_1 - 47.1\right)_1 + \left(M^1_1 + \frac{M^1_2 - M^1_1}{D_2 - D_1}(D - D_1) - 47.1_1.\right)$$

The expression (#)$_1$ gives the correction to the mean 47.1 due to the change of H from the mean value 61.1 to the given value H. The expression (#)$_2$ gives the correction required if the dew point differs from 45.6.

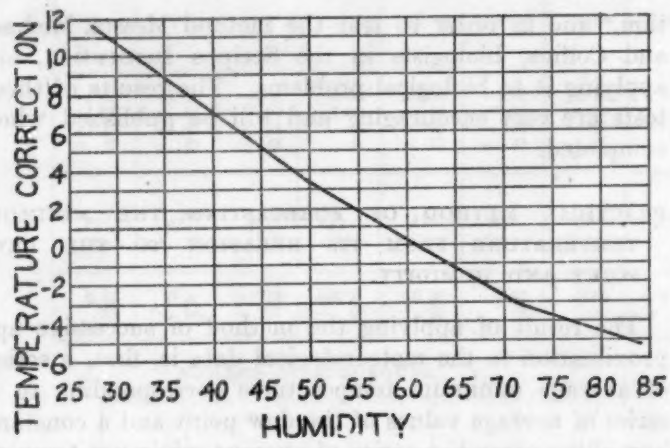

FIG. 1.—Graphic representation of the relation of the minimum temperature to the humidity, assuming the dew point to be constant.

The corrections are represented graphically by figures 1 and 2.

The relation is evidently not linear either to the humidity or to the dew point.

Finally, a more convenient method of determining M, using a single diagram, can be worked out as follows: (See Fig. 3.) Draw three parallel lines, the second one being equidistant from the other two. Represent minimum temperatures by distances on the middle line, using any convenient scale and origin, and enter the series of temperatures opposite the corresponding points. Draw a line through the average temperature (47.1 in this case) perpendicular to the three parallel lines. Using the intersection of this line with the first and second lines as origins, lay off corrections to the mean temperature, using *double* the scale adopted for the middle line. Positive corrections are represented by points above these origins and negative corrections by points below. (These points are not shown in the diagram.) Next, from the expression (#)$_1$ of the

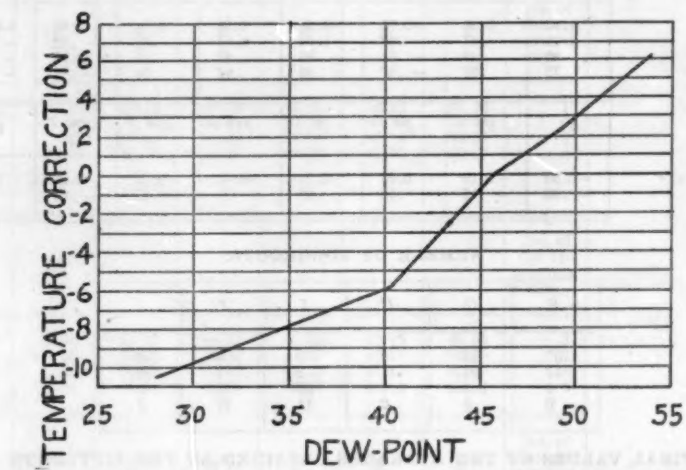

FIG. 2.—Graphic representation of the relation of the minimum temperature to the dew point, assuming the humidity to be constant.

formula on this page, or from figure 1, compute the corrections due to the humidities 26, 28, 30, etc., to 90; mark the positions on the first scale corresponding to these corrections, and enter the corresponding humidity figures opposite these marks, as shown in figure 3. In the same way compute the corrections due to the dew points 25, 26, 27, etc., to 55, using the expression (#)$_2$ of the formula on this page, or figure 2; mark on the third line the positions representing these corrections, and enter the corresponding dew-point figures opposite these marks, as shown in the diagram (fig. 3). To use the diagram in predicting the minimum temperature, apply a straight edge to the points corresponding to the given values of the humidity and dew point. The intersection with the middle line gives the temperature. If, for example, the humidity is 46 per cent and the dew point is 35°, the expected minimum temperature is 44°.

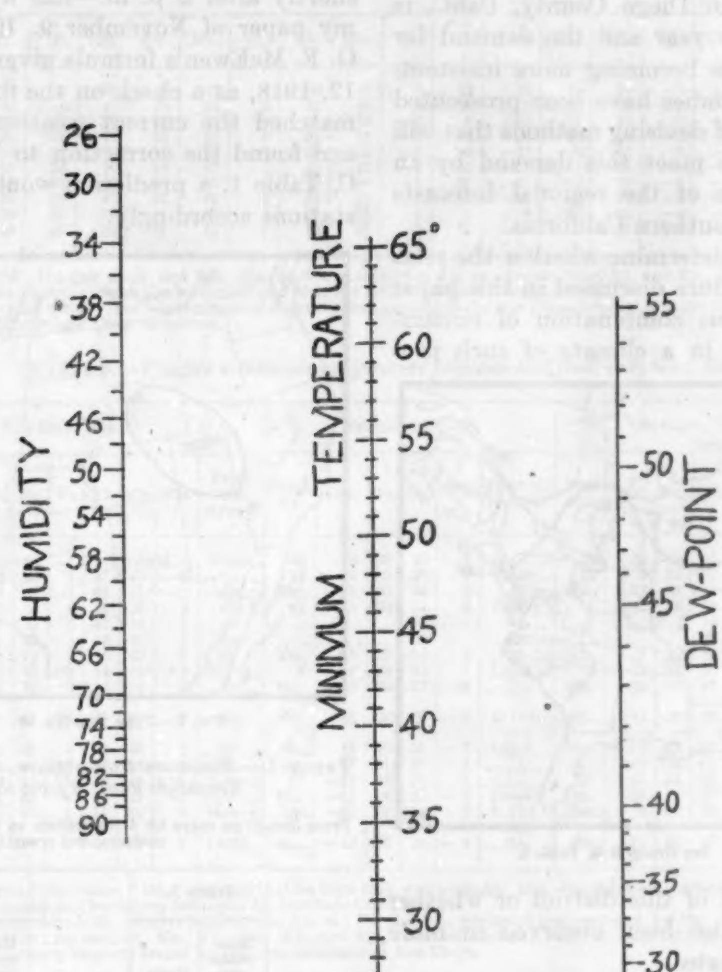

FIG. 3.—Diagram for predicting the minimum temperature from the dew point and the humidity.

NEW METHODS OF PREDICTING ORCHARD TEMPERATURES IN THE SAN DIEGO CITRUS DISTRICT.

By Henry F. Alciatore, Meteorologist.

[Dated: Weather Bureau, San Diego, Calif., Sept. 18, 1919.]

Synopsis.—"It is the object of this paper to describe a number of new methods of predicting orchard temperatures devised by the writer, based upon the evening hygrometric conditions at a base station in their relationship to the minimum temperature of the next day at orchard stations and to compare the results thus obtained with those of other investigators."

The citrus industry of San Diego County, Calif., is growing in importance every year and the demand for close temperature forecasts is becoming more insistent. With this in mind, further studies have been prosecuted at this office for the purpose of devising methods that will enable the local forecaster to meet this demand by an amplification or modification of the regional forecasts issued at San Francisco for southern California.

It would be of interest to determine whether the relations of humidity to temperature discussed in this paper are the result of a fortuitous combination of circumstances to be expected *only* in a climate of such pronounced equableness as that of this district or whether similar relationships have also been observed in more rigorous and changeable climates.

Fig. 1.—Type map No. 26. See Group B in Table 1.

Our first study was an attempt to correlate morning frost-type maps and evening hygrometric data of one day with the minimum temperature of the next at San Diego, taken as a base station, and a number of orchard stations in the same county. A number of such maps for five Novembers was divided into three groups, according to the temperature differences noted in past seasons between the base station and Escondido, as indicated in Table 1. Temperature records for these five years showed that ordinarily the rural station minima bore to one another a relation such as that shown below:

	°F.
Escondido, Calif.	38
El Cajon, Calif.	40
Bonita, Calif.	43

The temperature at El Cajon averages about 2°, and at Bonita about 5°, higher than that of Escondido. In addition to barometric data, each map also showed the succeeding day's minimum temperatures for all stations in the district and the regional frost-warning issued the day before. (See type maps, figs. 1 and 2.) In actual practice two forecasts for the base station would be made shortly after 5 p. m.—one by the method described in my paper of November 9, 1918, and the other by Dr. G. F. McEwen's formula given in his paper of November 12, 1918, as a check on the first forecast. Then, having matched the current weather map with the type map and found the correction to be applied, group A, B, or C, Table 1, a prediction would be made for the orchard stations accordingly.

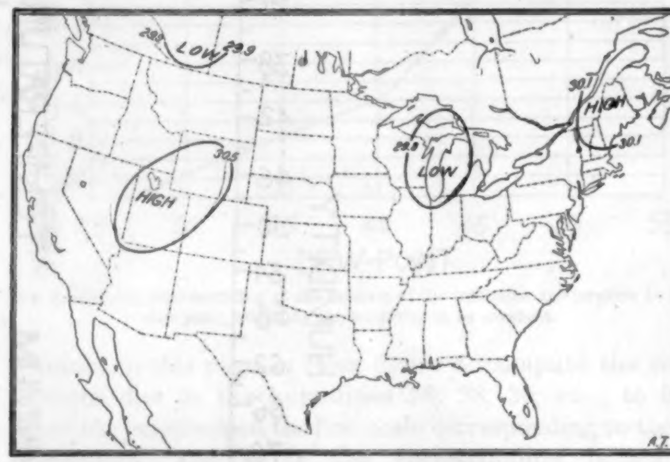

Fig. 2.—Type map No. 19. See Group C. in Table 1.

Table 1.—*Minimum temperatures at San Diego and variations of the Escondido minima from the base-station minima.*

From frost-type maps for 5 Novembers to 1917. Group A, showing small; group B, medium; and group C, large variations.]

Group A.			Group B.			Group C.		
Map No.	Minimum temperature next day at San Diego.	Variations at Escondido.	Map No.	Minimum temperature next day at San Diego.	Variations at Escondido.	Map No.	Minimum temperatures next day at San Diego.	Variations at Escondido.
1	43	−13	2	45	−16	12	52	−19
3	42	−12	7	49	−15	17	48	−18
4	42	−13	11	48	−16	18	49	−21
6	48	−14	14	50	−17	19	48	−18
8	45	−11	16	39	−16	20	51	−18
9	46	−14	21	49	−16	24	47	−18
28	46	−14	23	47	−17	35	49	−18
31	45	−13	25	44	−15	36	52	−19
32	42	−10	26	47	−15	38	49	−18
33	48	−14	27	46	−17			
			30	48	−16			
			34	48	−16			
			39	48	−15			
			40	46	−17			
Mean	....	−13	Mean	....	−16	Mean	....	−19

Note.—In group A, map No. 1, for example, −13 means that the minimum at Escondido was 13° lower than the base-station minimum.

A test was made for 10 days of November, 1918, the results of which appear in detail in Table 2. The fore-

casts for San Diego and Escondido were good, as 90 per cent of them were verified. At El Cajon and Bonita, however, the forecasts were poor, only five of the former and four of the latter having been verified, due to the fact that a large number of abnormal temperatures were recorded at those stations.

maps and no very marked resemblance at that. At Escondido, for example, our chance of matching maps was about 46 in 100. Two of the December frost-type maps (figs. 1 and 2) deserve special mention in that they seem to indicate that in their frost-predicting work some forecasters are much affected by what might be termed

TABLE 2.—*Trial minimum-temperature forecasts, November, 1918.*

Day.	Regional warning.	San Diego.*									Map No.	Escondido.**				El Cajon.**				Bonita.**			
		T.	DP.	RH.	Fa.	Ma.	Va.	Fb.	Mb.	Vb.		Cor.	Fc.	Mc.	Vc.	Cor.	Fd.	Md.	Vd.	Cor.	Fe.	Me.	Ve.
7	Heavy to killing	63	49	60	50	47	3	50	47	3	38	−19	31	34	−3	−13	37	35	2	−13	37	38	−1
8	Heavy	66	46	47	53	51	2	52	51	1	21	−16	37	35	2	−13	40	33	7	− 9	44	39	5
9	.....do	70	36	29	54	54	0	51	54	−3	6	−13	41	38	3	−13	41	35	6	− 9	45	40	5
11	Light to heavy	66	58	74	51	51	0	54	51	3	21	−16	35	38	−3	−13	38	37	1	− 9	42	38	4
16	Severe	64	55	72	52	55	−3	52	55	−3	9	−13	39	42	−3	−11	41	42	−1	− 9	43	43	0
26	Heavy	60	39	46	44	47	−3	46	47	−1	32	−13	31	34	−3	−10	34	38	−4	− 9	35	39	−4
27	Severe	59	46	62	48	48	0	47	48	−1	31	−13	35	38	−3	−13	35	41	−6	− 3	45	37	8
28	.....do	58	37	45	44	42	2	45	42	3	X	−16	28	29	−1	−13	31	29	2	− 9	35	33	2
29	.....do	50	46	62	48	43	5	47	43	4	4	−13	35	36	−1	−13	35	31	4	− 9	39	33	6
30	.....do	50	45	59	46	45	1	47	45	2	X	−16	30	35	−5	−13	33	36	−3	− 9	37	35	2

* T. is the dry bulb temperature; DP., the dew point; and RH., the relative humidity at 5 p. m., Pacific time; Fa. and Fb., the forecasts made by the Alciatore and McEwen methods, respectively; Va. and Vb., the variations from the predicted, and Ma., the actual minimum temperature.

** Map No. indicates the map chosen for the day; Cor., the amount of the correction applied to the San Diego forecast to make the substation forecast, and the other columns the predicted and actual minimum temperatures, and their variations.

TABLE 3.—*Practice minimum-temperature forecasts and frost warnings, December, 1918.*

Day.	Warning issued.	San Diego, Calif.										Escondido, Calif.						El Cajon, Calif.						Bonita, Calif.					
		T.	DP.	RH	Fa.	Ma.	Va.	Fb.	Mb.	Vb.	Frost observed.	Map No.	Cor.	Fc.	Mc.	Vc.	Frost observed.	Map No.	Cor.	Fd.	Md.	Vd.	Frost observed.	Map No.	Cor.	Fe.	Me.	Ve.	Frost observed.
3	Light to heavy.	71	28	20	52	53	−1	No data.			None.	25	−19	33	40	− 7		25	−16	36	38	−2		25	−10	42	40	2	
9	.....do	59	51	75	48	47	1	47	47	0	..do	12	−13	35	36	− 1	Light	12	− 9	39	39	0		Mn.	−10	38	40	−2	
13	Light	60	29	45	45	47	−2	46	47	ᵃ−1	..do	Mn.	−15	30	34	− 4		Mn.	−12	33	35	−2	Light	..do..	−10	35	38	−3	
16	Light to heavy	61	51	72	49	44	5	48	44	4	..do	1	−15	34	34	0	Heavy	1	−10	30	36	3		..do..	−10	39	36	3	
18	None	58	48	69	48	46	2	47	46	1	..do				32		...do				38						40		
21	.....do	52	44	76	36	41	−5	42	41	1	..do				32		...do				36						35		
22	Severe	57	38	48	44	42	2	45	42	3	..do	Mn.	−15	29	32	3	...do	Mn.	−12	32	34	2	Light	Mn.	−10	34	36	2	
23	Heavy	56	42	58	44	42	2	44	42	ᵇ2	Light.	2	−19	25	32	7	Light	2	−12	32	30	2	Heavy	..do..	−10	34	31	3	Light.
24	Light to heavy.	56	34	44	39	39	0	44	39	5	..do	Mn.	−15	24	37	−13		Mn.	−12	27	28	−1	Killing.	..do..	−10	29	28	1	
25	Heavy	57	33	40	41	37	4	45	37	8	..do	..do..	−15	26	28	− 2	Killing.	..do..	−12	29	26	3	...do	..do..	−10	31	30	1	
26	Light to heavy.	58	43	58	44	40	4	45	40	5	..do	..do..	−15	29	31	− 2	Light	..do..	−12	32	30	2	Heavy	..do..	−10	34	31	3	Heavy.
27	.....do	60	49	69	46	46	0	47	46	1	..do	..do..	−15	31	35	− 4		..do..	−12	34	32	2	Light	..do..	−10	36	35	1	
28	Light	59	55	86	49	48	1	49	48	1	None..	27	−15	34	31	3		27	−12	37	32	5	...do	27	−10	39	34	5	
29	Light to heavy.	55	45	68	41	46	−5	44	46	−2	..do	Mn.	−15	26	30	− 4	Heavy	Mn.	−12	29	37	−8		Mn.	−10	31	39	8	
30	Light	53	30	40	36	35	1	44	35	9	Heavy	. do..	−15	21	24	− 3	Killing.	..do..	−12	24	28	−4	Light	..do..	−10	26	29	−3	Light.
31	Light to heavy.	53	30	41	35	35	0	44	35	9	Light..	..do..	−15	20	24	− 4	...do	..do..	−12	23	27	−4	Heavy	..do..	−10	25	28	−3	Heavy.

NOTE.—In columns entitled "Map No." the letters "Mn." indicate that no type map was available, and that the mean variation was used for correction.
The "warnings issued" were those issued by the district forecaster for Southern California.
T is current temperature; D P., dew point; R H., relative humidity at 5 p. m.; Fa. and Fb., predicted temperatures by the Alciatore and McEwen methods, respectively; Fc., Fd., and Fe., predictions by the type map method; Ma., Mb., Mc., Md., and Me., observed minima; Va., Vb., Vc., Vd., Ve., variations from the actual minima.
ᵃ and ᵇ were special minimum-temperature forecasts issued by the local forecaster at San Diego.

As this scheme did not prove satisfactory at all places, a second test of the frost-type map method was made in December, 1918, but instead of using one table of corrections for all stations we used three such tables, one for each place, as shown in Table 3. Here it was assumed that a current map such as frost-type map No. 6 (Table 3) would be followed the next morning by minimum temperatures 11° lower at Escondido and 9° lower at El Cajon, than the predicted minimum temperature for San Diego. Still another assumption was made, namely, that in a series of, say, four or five Decembers (120 to 150 maps) a given pressure distribution on the Pacific slope of the frost-producing type would be followed in most cases by a certain degree of cold in this district. In this we were disappointed, however, as we found only five type maps bearing a resemblance to the current

the *high-pressure myth;* that is, the notion that all other things being equal, *the higher the pressure the colder the weather*. For example, map No. 26 shows a modest looking HIGH overlying the north Pacific district with central pressure of about 30.2 inches. The fact that the warning for southern California based upon this map was for *light frost* proves that our contention is soundly based, for it was followed the next morning by as severe a freeze as we ever experience in this region in December, i. e., minimum temperatures of 39° F. at San Diego, 23° F. at Escondido, 28° F. at El Cajon, and Bonita, 25° F. Evidently there are other factors besides the *intensity* of HIGHS (geographical coordinates, for instance) that enter into the problem of frost predictions. In marked contrast to No. 26, let us consider map No. 19, with a much more energetic HIGH over Utah, and a cen-

tral pressure of about 30.5 inches, which was followed by another freeze of almost the same degree of severity, namely, minima of 40° F. at San Diego, 21° F. at Escondido, 24° F. at El Cajon, and 29° F. at Bonita. In this case the regional frost warning was *killing frost*. Now, should the reader ask: "Why this great difference between the two warnings?" I would answer: The high-pressure myth. In the face of such facts, which are seldom, if ever, mentioned in weather-forecasting manuals, what shall be said of the advantages (?) of 2, 12, or 24-hour pressure-change charts for frost-forecasting work?

The district and local frost-warnings issued, predicted and observed temperatures, etc., for December, 1918, are given in detail in Table 3, which shows that the temperature predictions for El Cajon and Bonita were good; those for San Diego fair, and for Escondido poor. The low verification percentage at Escondido may have been due to the occurrence of temperature reversals (relatively to El Cajon), which are caused, we think, by local winds, a subject that needs to be investigated. Only two minimum-temperature predictions were actually made and issued by the local forecaster (the writer hereof). The variations of the predicted from the observed temperatures are given below:

	Date of forecast.	
	Dec. 13.	Dec. 23.
	° F.	° F.
San Diego	−2	2
Escondido	−4	7
El Cajon	−2	2
Bonita	−3	3

In each instance three out of four were verified, but the large variation at Escondido in the prediction of December 23 brought my local forecast activities to an end, as it was then evident that the frost-type map method was not very reliable.

An investigation of the 24-hour changes in the minimum temperatures recorded at the base and substations for several Decembers has convinced us that these are at times very erratic. On more than half of the days studied the sign of the change was plus at some stations and minus at the others. One morning the minimum temperature rose 2° at Bonita and fell 8° at Escondido. This is one of the things that makes close temperature forecasting so difficult an undertaking.

As an improvement on the frost-type map method, a new scheme was devised in March, 1919, introducing the 5 p. m. dry-bulb temperatures at the base station, as it was observed that their relation to the minima of the following day at Escondido was more stable than any other so far studied. The hygrometric data were grouped in a different manner. Table 4 shows the arrangement for a period of six Januarys to 1918. From these values we computed progressive means of dry-bulb temperatures for San Diego and for depressions of the minimum temperature at Escondido and El Cajon. Table 5 gives the results in detail. For example, in group B, an increase of 2° in the base station temperature is associated with increases of 2° at Escondido, and 3° at El Cajon in the depression of the next day's minima below the base station values. This relation forms the basis of the new method—we shall call it "The 5 p. m. temperature method." To illustrate it, let us take the forecast of January 6, 1919. The 5 p. m. temperature and humidity values for San Diego were:

Dry-bulb temperature	63° F.
Dewpoint	32° F.
Relative humidity	31 per cent.

TABLE 4.—*Evening dry-bulb temperature, dew point, and relative humidity (5 o'clock) at San Diego, Calif. (key station), and observed minimum temperatures the next morning at Escondido, El Cajon, and Bonita, Calif., and depression of the minimum temperature below the San Diego evening dry-bulb temperature at rural stations.*

(Only for evenings preceding mornings with freezing or lower temperatures at rural stations.)

Year.	Day.	San Diego.			Escondido.		El Cajon.		Bonita.	
		T.	DP.	RH.	M.	V.	M.	V.	M.	V.
GROUP A.—DEW POINT, −1° TO 29°; RELATIVE HUMIDITY, 13 TO 32 PER CENT.										
1913	6	42	−1	13	13	−29	21	−21	......	......
1913	7	48	26	41	18	−30	19	−29	......	......
1915	16	58	29	32	27	−31	27	−31	......	......
GROUP B.—DEW POINT, 30° TO 39°; RELATIVE HUMIDITY, 47 PER CENT OR OVER.										
1913	11	50	39	54	27	−23	29	−21	......	......
1916	11	51	33	50	27	−24	29	−22	30	−21
1913	8	52	38	58	26	−26	28	−24	......	......
1916	12	53	34	50	29	−24	31	−22	33	−20
1918	10	56	36	47	26	−30	27	−29	31	−25
GROUP C.—DEW POINT, 30° TO 39°; RELATIVE HUMIDITY, 46 PER CENT OR LESS.										
1913	13	58	37	46	31	−27	32	−26	......	......
1918	23	58	35	42	29	−29	29	−29	33	−25
1913	24	63	30	29	32	−31	31	−32	......	......
1915	19	64	33	32	28	−36	30	−34	......	......
GROUP D.—DEW POINT, 40° TO 49°; RELATIVE HUMIDITY, 65 PER CENT OR OVER.										
1913	10	48	40	73	27	−21	29	−19	......	......
1917	3	54	48	84	32	−22	31	−23	37	−17
1913	4	54	46	76	32	−22	30	−24	......	......
1917	22	56	44	65	29	−27	30	−26	33	−23
1918	30	56	44	65	32	−24	32	−24	40	−16
1915	9	57	46	66	31	−26	32	−25	......	......
1918	11	57	46	65	31	−26	29	−28	34	−23
GROUP E.—DEW POINT, 40° TO 49°; RELATIVE HUMIDITY, 64 PER CENT OR LESS.										
1913	23	54	42	64	29	−25	31	−23	......	......
1917	23	54	42	63	31	−23	29	−25	33	−21
1913	21	55	40	57	29	−26	31	−24	......	......
1915	18	58	42	56	30	−28	30	−28	......	......
1915	15	58	41	54	29	−29	30	−28	......	......
1913	20	58	45	61	26	−32	26	−32	......	......
1914	12	59	46	62	28	−31	31	−28	......	......
1918	22	59	43	55	30	−29	27	−32	34	−25
1917	24	62	43	51	32	−30	32	−30	34	−28
GROUP F.—DEW POINT, 50° TO 59°; RELATIVE HUMIDITY, 83 PER CENT OR OVER.										
1917	13	52	51	97	31	−21	35	−17	36	−16
1918	5	54	52	91	31	−23	34	−20	45	−9
1915	14	58	53	83	32	−26	37	−21	......	......

TABLE 5.—*Progressive means of 5 p. m. dry-bulb temperatures at San Diego (key station) and of depression of next morning's minimum temperatures below the 5 p. m. temperature of San Diego, for Escondido and El Cajon, Calif., for six Januarys, 1913 to 1918, for groups A, B, C, D, E, and F of Table 1.*

(For use in making tentative forecasts of minimum temperature at rural stations.)

GROUP A.

San Diego.			Escondido.			El Cajon.		
T.	Sum.	PM.	V.	Sum.	PM.	V.	Sum.	PM.
42	42	42	−29	− 29	−29	−21	−21	−21
48	90	45	−30	− 59	−30	−29	−50	−25
58	148	49	−31	− 90	−30	−31	−81	−27
Range.....		7	....	....	1	....	....	6

GROUP B.

San Diego.			Escondido.			El Cajon.		
T.	Sum.	PM.	V.	Sum.	PM.	V.	Sum.	PM.
50	50	50	−23	− 23	−23	−21	− 21	−21
51	101	50	−24	− 47	−24	−22	− 43	−22
52	153	51	−26	− 73	−24	−24	− 67	−22
53	206	52	−24	− 97	−24	−22	− 89	−22
56	262	52	−30	−127	−25	−29	−118	−24
Range.....		2	....	....	2	....	....	3

GROUP C.

San Diego.			Escondido.			El Cajon.		
T.	Sum.	PM.	V.	Sum.	PM.	V.	Sum.	PM.
58	58	58	−27	− 27	−27	−26	− 26	−26
58	116	58	−29	− 56	−28	−29	− 55	−28
63	179	60	−31	− 87	−29	−32	− 87	−29
64	243	61	−36	−123	−31	−34	−121	−30
Range.....		3	....	....	4	....	....	4

GROUP D.

San Diego.			Escondido.			El Cajon.		
T.	Sum.	PM.	V.	Sum.	PM.	V.	Sum.	PM.
48	48	48	−21	− 21	−21	−19	− 19	−19
54	102	51	−22	− 43	−22	−23	− 42	−21
54	156	52	−22	− 65	−22	−24	− 66	−22
56	212	53	−27	− 92	−23	−26	− 92	−23
56	268	54	−24	−116	−23	−24	−116	−23
57	325	55	−26	−142	−24	−25	−141	−24
57	382	55	−26	−168	−24	−28	−169	−24
Range.....		7	....	....	3	....	....	5

GROUP E.

San Diego.			Escondido.			El Cajon.		
T.	Sum.	PM.	V.	Sum.	PM.	V.	Sum.	PM.
54	54	54	−25	− 25	−25	−23	− 23	−23
54	108	54	−23	− 48	−24	−25	− 48	−24
55	163	54	−26	− 74	−25	−24	− 74	−24
58	221	55	−28	−102	−25	−28	−100	−25
58	279	56	−29	−131	−26	−28	−128	−26
58	337	56	−32	−163	−27	−32	−160	−27
59	396	57	−31	−194	−28	−28	−188	−27
59	455	57	−29	−223	−28	−32	−220	−28
62	517	57	−30	−253	−28	−30	−250	−28
Range.....		3	....	....	3	....	....	5

GROUP F.

San Diego.			Escondido.			El Cajon.		
T.	Sum.	PM.	V.	Sum.	PM.	V.	Sum.	PM.
52	52	52	−21	− 21	−21	−17	− 17	−17
54	106	53	−23	− 44	−22	−20	− 37	−18
58	164	55	−26	− 70	−23	−21	− 58	−19
Range.....		3	....	....	2	....	....	2

T., is the 5 p. m. dry-bulb temperature at San Diego; PM., the progressive mean; V., the depression of the rural station minimum temperature below the 5 p. m. temperature of San Diego; the range is the difference between the first and last entries in the columns of progressive means.

This combination falls under group C, Table 5, in which an increase of 3° (58° to 61°) in the evening temperature of the base station indicates an increase of 4° in the depression of the Escondido minimum below that of the base station. Now, since the San Diego temperature, 63° F., is 5° higher than the initial entry of the table (58°), the expected variation at Escondido will be larger and, by proportion, we have: 4/3 times 5, equals 6.7°; the true correction to be applied is −27 (the initial value of the table) plus −6.7, or, −33.7. Finally, subtracting this quantity from 63 we get 29.3 for the probable minimum at Escondido for January 7. The observed temperature was 30°.

TABLE 6.—*Practice forecasts of minimum temperature for Escondido and El Cajon, Calif., for month of January, 1919, with variations of the observed from the predicted temperatures.*

[Forecasts made by the new "5 p. m. progressive mean temperature" method devised at the San Diego office.]

Day.	Frost warning.	San Diego.			Escondido.				El Cajon.			
		T.	DP.	RH.	C.	F.	M.	V.	C.	F.	M.	V.
1.....	Killing.........	53	36	52	−26	27	24	3	−25	28	33	(?)
2.....	.....do.........	55	31	30	−23	32	28	4	−22	33	31	2
3.....	.....do.........	66	22	18	−32	34	35	−1	−42	24	32	−8
5.....	None...........	64	37	36	−35	29	32	−3	−34	30	29	1
6.....	Heavy..........	63	32	31	−34	29	30	−1	−33	30	30	0
11....	None...........	59	55	85	−26	33	34	−1	−22	37	32	5
12....	.....do.........	58	50	74	−25	33	35	−2	−21	37	32	5
13....	Heavy..........	63	45	53	−34	29	48	(?)	−38	25	29	−4
14....	.....do.........	62	44	53	−33	29	31	−2	−36	26	25	(?)
15....	None...........	58	52	78	−25	33	31	2	−21	37	30	7
16....	.....do.........	58	50	74	−25	33	32	1	−21	37	30	7
25....	Light to heavy.	59	49	68	−26	33	33	0	−27	32	32	0
26....	None...........	61	50	70	−27	34	37	−3	−23	38	31	(?)
27....	Heavy..........	75	28	16	−34	41	43	−2	−49	26	31	−5

	Escondido.	El Cajon.
Total forecasts..	13	11
Satisfactory forecasts................................	12	4
Verification................................per cent..	92.3	36.4

T. is the 5 p. m. temperature; DP., dew point; and RH., relative humidity at San Diego (key station). C. is the correction applied to the San Diego temperature to obtain the probable minimum expected at the rural stations; F. is the predicted and M. the observed minimum temperature at rural stations; V. is the variation of the predicted from the observed minima.

A satisfactory forecast is one which comes within 3° (plus or minus) of the observed minimum temperature, as in all previous reports submitted by the writer, a purely arbitrary limit.

The month of January, 1919, was selected for a test. (See Table 6.) The salient features of this table were a remarkably high verification percentage (92.3) and an absurdly low one at El Cajon, 36.4. The latter, however, had but little to do with methods, for we discovered that the El Cajon observer had used uncorrected thermographic, instead of maximum and minimum thermometer readings, which, of course, are not comparable with the Escondido readings of the same period.

Table 7 shows the results of a comparative test of the accuracy of the writer's and McEwen's methods as applied to San Diego for January, 1919. The verification percentages were, respectively, 66.7 and 69.2.

TABLE 7.—*Practice forecasts of minimum temperature for San Diego, Calif., January, 1919, by the Alciatore and McEwen methods.*

Day.	T.	W.	DP.	RH.	Alciatore.			McEwen.		
					F.	M.	V.	F.	M.	V.
1.....................	53	45	36	52	39	35	4	42	35	7
2.....................	55	44	31	39	43	41	2	45	41	4
3.....................	66	47	22	18	43	45	−2	......	......	......
4.....................	62	54	47	60	49	49	0	48	49	−1
6.....................	63	48	32	31	50	45	5	48	45	3
7.....................	64	53	44	49	50	48	2	49	48	1
8.....................	67	51	36	33	50	52	−2	50	52	−2
13....................	63	54	45	53	50	44	6	49	44	5
14....................	62	52	44	53	48	45	3	48	45	3
24....................	57	55	53	87	48	52	−4	48	52	−4
25....................	59	53	49	68	47	46	1	48	46	2
27....................	75	53	28	18	55	50	5	48	50	−2
28....................	70	50	27	20	54	56	−2	......	......	......
29....................	65	55	47	52	53	53	0	51	53	−2
30....................	65	56	52	72	49	52	−3	49	52	−3

	Alciatore.	McEwen.
Total	15	13
Verified	10	9
Per cent verified ....per cent..	66.7	69.2

T. is the dry-bulb and W. the wet-bulb temperature; DP., dew point; RH., relative humidity; F. the predicted and M. the observed minimum temperature; V. the variation of the predicted from the observed temperature.

TABLE 8.—*Evening pressure, temperature, and hygrometric data for San Diego (base station), and the following morning's minimum temperature at Escondido and El Cajon, with the depression of the Escondido minimum below the base station 5 p. m. temperature and the depression of the El Cajon minimum temperature below the Escondido minimum, for six Februarys (1913 to 1918).*

(For days with minimum temperatures of 33° F. or lower at the rural stations, regardless of radiation conditions.)

Day.	Year.	5 p. m.				Next morning.			
		San Diego.				Escondido.		El Cajon.	
		P.	T.	DP.	RH.	M1.	V1.	M2.	V2.
18	1918	29.82	51	38	62	33	−18	37	4
19	1913	29.84	51	38	62	28	−23	31	3
1	1916	30.38	53	41	63	32	−21	33	1
12	1913	30.28	55	49	79	35	−20	32	−3
3	1915	30.21	55	45	70	33	−22	36	3
14	1917	30.15	56	49	74	33	−23	31	−2
2	1918	30.12	56	49	77	33	−23	33	0
2	1913	30.03	56	47	71	33	−23	33	0
14	1913	30.19	57	50	77	36	−21	32	−4
1	1918	30.15	57	46	65	30	−27	31	1
5	1918	30.03	57	44	62	32	−25	34	2
7	1914	30.08	58	45	61	30	−28	33	3
16	1918	30.07	59	48	68	32	−27	33	1
1	1914	29.96	60	50	70	33	−27	35	2
5	1917	30.06	60	49	68	35	−25	33	−2
8	1914	30.03	60	48	65	32	−28	35	3
1	1917	30.23	60	40	46	29	−31	34	5
2	1917	30.11	62	41	47	33	−29	35	2
10	1918	30.01	65	40	39	31	−34	31	0
Sum									19
Mean									1

P. is the barometric pressure, M. S. L.; T., dry-bulb temperature; DP., dew point; RH., relative humidity at San Diego (base station) at 5 p. m., Pacific time.
M1 and M2 are the next morning's minimum temperatures; V1 the depression of the Escondido minimum temperature below the San Diego evening dry-bulb temperature; V2, the depression of the El Cajon minimum temperature below the Escondido minimum temperature of the same day.

Up to this time, March, 1919, it looked as if the 5 p. m. temperature method was the most promising, but later, after another test, we found that it was not. Therefore, another scheme was tried in which we adhered to the 5 p. m. temperature of the base station as the starting point, but instead of arranging the data as in the preceding test we arranged them as shown in Table 8; also, instead of using the older scheme of predicting temperatures for the orchards, this time we first made an estimate for Escondido, and then another for El Cajon by adding 1° to all the predicted temperatures for Escondido, the records for six Februarys having shown that the minima (on cold mornings) at El Cajon averaged about 1° higher than at Escondido. (The barometric values are included in this table for what they may be worth.) Progressive means of 5 p. m. temperatures at San Diego and depressions at Escondido were also retained. (See Table 9, in which, opposite the word "Range," at the bottom, appear the figures 6 and 7.) These give us the ratio of the 5 p. m. temperature to the depression. For example, if the 5 p. m. temperature at San Diego is, say, 51° F., we may reasonably expect a minimum temperature the next day at Escondido about 18° lower, or 33° F.

By way of description of this latest method (which we shall call "The San Diego 5 p. m. temperature method"), let us consider two typical cases—one with a higher and one with a lower dry-bulb temperature than the initial tabular values in Table 9.

TABLE 9.—*Progressive means of evening dry-bulb temperatures at San Diego (base station), and depression of next morning's minimum temperature at Escondido below San Diego evening temperatures, for six Februarys (1913 to 1918).*

(For days with minimum temperatures of 33° F. or lower, at the rural stations, regardless of radiation conditions.)

Day.	Year.	San Diego (5 p. m).			Escondido (next morning).		
		T.	Sum.	PM.	V1.	Sum.	PM.
18	1918	51	51	51	−18	− 18	−18
19	1913	51	102	51	−23	− 41	−20
1	1916	53	155	51	−21	− 62	−21
12	1913	55	210	52	−20	− 82	−20
3	1915	55	265	53	−22	−104	−21
14	1917	56	321	54	−23	−127	−21
2	1918	56	377	54	−23	−150	−21
2	1913	56	433	54	−23	−173	−22
14	1913	57	490	54	−21	−194	−22
1	1918	57	547	55	−27	−221	−22
15	1918	57	604	55	−25	−246	−22
7	1914	58	662	55	−28	−274	−23
16	1918	59	721	55	−27	−301	−23
1	1914	60	781	56	−27	−328	−23
5	1917	60	841	56	−25	−353	−23
8	1914	60	901	56	−28	−381	−24
1	1917	60	961	56	−31	−412	−24
2	1917	62	1,023	57	−29	−441	−24
10	1918	65	1,088	57	−34	−475	−25
Range				6			7

P. is the 5 p. m. dry-bulb temperature; PM., progressive means; range, difference between the first and last values.

For the forecast of February 2 we have dry-bulb temperature, 53° F.; ratio, 7/6. As the given temperature (53°) is 2° above the initial table temperature (51°) we take 7/6 of that quantity (−2.3) and add it to the tabular correction (−18). This gives −20.3 as the total correction; and, finally, 53°−20.3°, or 32.7° F., is the temperature sought.

For the forecast of February 3, dry-bulb temperature, 50° F. This being 1° *lower* than the initial tabular value (51°), obviously the correction should be smaller; therefore, 7/6 of 1 added to −18, or −16.8, is the total correction, and 50° minus 16.8°, or 33.2° F., is the temperature expected. Forecasts were made for 16 other days of February, 1919, by this method, as shown in detail in Table 10, to which we have added regional frost warnings, and frosts actually observed, for the purpose of calling attention to an interesting phase of forecasting work, namely, that in every instance where the method failed completely (four times at Escondido and six at El Cajon) subsequent events showed that no frost warnings should have been made as the temperatures actually recorded were abnormally high. Therefore, as our method was devised for use only when low temperatures are expected, Table 10 contains two sets of verification percentages (*a*) for all the days in the table, regardless of warnings, and (*b*) for days on which warnings would have been justified. These are compared below:

Verification percentages, February, 1919.

	Escondido.	El Cajon.
	Per cent.	*Per cent.*
(*a*)	77.8	55.6
(*b*)	100.0	83.3

TABLE 10.—*Practice minimum-temperature forecasts for Escondido and El Cajon, Calif., for February, 1919, with variations of the predicted from the observed minimum temperatures.*

(Forecasts made by the improved "5 p. m. progressive mean temperature" method devised at the San Diego Weather Bureau office.)

Day.	Warning.	Escondido. T.	C.	F1.	M1.	V1.	OF.	El Cajon. F1.	C.	F2.	M2.	V2.	OF.
2	None	53	−20	33	35	−2	L.	33	1	34	35	−1	None.
3	L. to H	50	−17	33	32	1	L.	33	1	34	34	0	L.
4	do	57	−25	32	38	−6	....	32	1	33	42	−9	None.
5	H	57	−25	32	40	−8	....	32	1	33	47	−14	Do.
6	L. to H	60	−28	32	44	−12	....	32	1	33	47	−14	Do.
11	None	54	−22	32	33	−1	L.	32	1	33	42	−9	Do.
12	L. to H	57	−25	32	32	0	L.	32	1	33	35	−2	L.
13	do	58	−26	32	33	−1	H.	32	1	33	35	−2	Do.
15	do	57	−25	32	35	−3	L.	32	1	33	35	−2	Do.
17	None	55	−23	32	33	−1	L.	32	1	33	41	−8	None.
18	L. to H	58	−26	32	33	−1	L.	32	1	33	38	−5	Do.
19	do	57	−25	32	40	−8	....	32	1	33	44	−11	Do.
20	L	55	−23	32	30	2	H.	32	1	33	35	−2	Do.
21	L. to H	58	−26	32	33	−1	L.	32	1	33	39	−6	Do.
23	None	54	−22	32	31	1	H.	32	1	33	34	−1	Do.
24	L. to H	56	−24	32	29	3	K.	32	1	33	30	3	H.
25	L	59	−27	32	29	3	H.	32	1	33	30	3	Do.
27	L. to H	57	−25	32	33	−1	....	32	1	33	35	−2	None.
Good forecasts							14						10
Total made							18						18
Verification (a)		per cent					77.8						55.6
Good forecasts							14						10
Total made							14						12
Verification (b)		per cent					100.0						83.3

T. is the evening temperature at San Diego (key station); C., correction; F1 and F2, predicted temperatures; M1 and M2, observed temperatures; V1 and V2, variations of the predicted from the observed temperatures at Escondido and El Cajon, respectively; OF., observed frosts, L. for light, H. for heavy, and K. for killing frosts. The "warning" is that issued for southern California. "None," or absence of letters, indicates no frosts observed or warnings issued.

TABLE 11.—*Practice forecasts of minimum temperature for San Diego, Calif., by the Alciatore and McEwen methods described in preceding papers, for February, 1919.*

(For days on which the regional frost warnings which were received from the district forecaster applied to San Diego City.)

Day.	Warning.	T.	DP.	RH.	Alciatore. F1.	M1.	V1.	McEwen. F2.	M1.	V2.	OF.
3	L. to H	55	45	69	41	43	−2	44	43	1	None.
4	do	57	48	71	46	48	−2	46	48	−2	Do.
12	do	57	46	64	43	44	−1	47	44	3	Do.
13	do	58	49	73	44	48	−4	46	48	−2	Do.
15	do	57	49	74	44	46	−2	46	46	0	Do.
18	L	58	46	63	47	43	4	47	43	4	Do.
21	do	58	44	59	45	48	−3	46	48	−2	Do.
24	do	56	40	52	43	41	2	44	41	3	L.
Total							8				8
Verified							6				7
Per cent verified							75				87.5

The warning is that issued for southern California. T. is the dry-bulb temperature; DP., dew point; and R.H., relative humidity at 5 p. m.; F1 and F2 are the predicted, and M1 is the observed, minimum temperature; V1 and V2 the variations of the predicted from the observed minimum temperatures; L. indicates a light and H. a heavy frost; OF. indicates the kind of frost observed next morning.

TABLE 12.—*Comparative statement of verification percentages of minimum-temperature forecasts made by different methods, for San Diego (A), Escondido (B), El Cajon (C), and Bonita (D).*

Month and year.	Method used by H. F. Alciatore.	Verification percentages. (A.)	(B.)	(C.)	(D.)
November, 1918	Statistical	90			
	Frost-type maps		90	50	40
	By G. F. McEwen, formula	90			
	By Prof. J. W. Smith, formula	90			
December, 1918	By H. F. Alciatore, statistical	69			
	Frost-type maps		50	71	86
	By G. F. McEwen, formula	60			
January, 1919	By H. F. Alciatore:				
	Statistical	67			
	5 p. m. method		92	36	
	By G. F. McEwen, formula	69			
February, 1919	By H. F. Alciatore:				
	Statistical	75			
	5 p. m. method		100	83	
	By G. F. McEwen, formula	88			
November, 1918	By Prof. J. W. Smith, formula No. 2	70			
December, 1918	By Prof. J. W. Smith, formula No. 1	69			
January, 1919	do	78			
February, 1919	do	100			

NOTE.—A forecast is considered as verified if the predicted comes within 3° or less of the observed temperature.

This suggests another idea, namely, that no matter what the method used, be it purely statistical or purely mathematical, after all, success or failure must depend largely upon a correct or incorrect diagnosis of the cold-weather symptoms found in the morning weather map. This criticism is, we believe, of general application in frost-forecasting work. The results obtained by the last-method described seem all the more surprising in that the basis of the forecast was a dry-bulb temperature obtained from an instrument exposed on the roof of a public building (United States post office) in San Diego, 62 feet above the street. A comparison of verification percentages for predictions made by the statistical and mathematical methods in February, 1919, appears in Table 11. The final values were 75 per cent for the former and 87.5 per cent for the latter. As to these two methods it might be said that in general the differences in such percentages seem to depend on whether the current hygrometric data approximate more closely to the tabular values of the first or the graphic values of the last-named method. Another point that might be made is that in all tests for San Diego temperatures the same tabular values were used, i. e., the means for 21 Decembers, from which circumstance we are tempted to conclude that the relationships cited in preceding para-

graphs are not peculiar to December alone. Otherwise, how could we explain the fact that by actual trial satisfactory forecasts were made for other months, such as November, January, and February, based upon the December hygrometric normals?

A summary of verification percentages for all the methods that have so far been tried out is given in Table 12. There is one thing about forecasting schemes which, we think, should be emphasized, namely, that all the schemes actually in use or that have been proposed have at least one inherent defect in common, i. e., the probability of complete failures at critical times—that is, when large "accidental" variations such as have been mentioned in this and in other papers occur in actual practice.

CONCLUSIONS.

1. All the methods tested but one seem to be sufficiently promising to warrant a trial this winter, despite the fact that none can be said to be entirely free from one common and serious defect, i. e., the probability of complete failure on certain occasions due to unforeseeable causes of a local nature.

2. For making predictions at the base station (San Diego) Prof. Smith's formulas gave much the best results. The McEwen and Alciatore methods differed but little from each other as to accuracy of results; the final percentages of successful forecasts were 81.4, 76.8, and 75.2, respectively.

3. The method tested in February, 1919, was the only one that proved good for all the rural stations. At Escondido, three out of four methods gave good results, and this indicates that it might be well to make original forecasts for the base station and Escondido *only*, and then predict for El Cajon and Bonita afterwards, by applying suitable corrections to the Escondido estimate. Also that since there are now several methods available for predicting for San Diego, the mean of several estimates would probably prove more reliable than a single estimate, no matter what the method used.

4. Too much weight seems to have been given in the past to intensities of high-pressure areas. It is doubtful if 2, 12, or 24 hour pressure change maps are of importance in forecasting frosts.

5. The frost-type maps were somewhat disappointing.

6. A thorough investigation of hygrometric conditions at the orchard stations themselves might profitably be undertaken with the view of correlating them with similar data at the base station.

7. After all, success or failure in temperature predicting will continue to depend largely upon the correct or incorrect diagnosis of the cold-weather symptoms of the morning weather map, and to a smaller extent, (*a*) local winds and sky conditions; (*b*) personal errors in thermometer readings, and instrumental errors; (*c*) the occasional advent of the frost-producing anticyclonic area at Escondido (the most northerly station) one or more hours earlier than at points farther south.

[illegible]PHY.

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